Implementation of digital dental radiography

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User aspects, radiation dose and diagnostic effects

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User aspects, radiation dose and diagnostic effects

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General introduction

INTRODUCTION

Only three months after the coincidental discovery of 'X'-rays by Wilhelm Conrad Röntgen in November 1895, the first dental radiograph was made by Otto Walkhoff, dentist in Braunschweig, Germany. Walkhoff placed a small glass photographic plate coated with rubber dam in his own mouth, then seated himself for a *twenty-five minute* exposure to the rays (Figure 1). Although the resulting shadows were less than adequate for any diagnostic purposes, the possible applications of the technique were clear. One month later Wilhelm König reduced the exposure time to nine minutes en produced radiographs of his front teeth of much better diagnostic quality (Figure 2). The realization of the harmful side of the rays followed soon after. Technology, however, further improved and dental radiography became an established diagnostic method.

Figure 1. Walkhoff

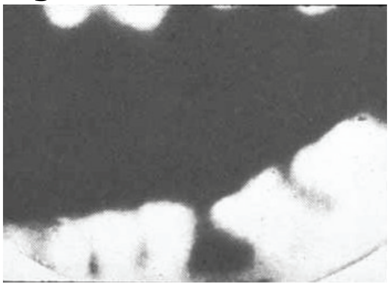
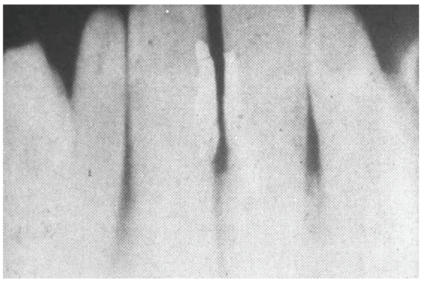


Figure 2. König



In 1987 the unchallenged status of X-ray sensitive film as the only image receptor for dental radiography was attacked by the first *digital* image receptor: the 'RadioVisioGraphie' system, including a CCD (Charge Coupled Device) and processing unit, displaying the digital image on a television monitor.[1,2]

Another digital imaging technique, storage phosphor radiography, first introduced in medical radiography in 1981 became available for intra-oral imaging in 1994.[3,4]

When switching from film based radiography to digital radiography the dentist is confronted with changes in the way he is practicing dentistry in every respect. It starts with the acquisition of radiographic images. One and the same digital image receptor will be used in a dental clinic for years for all patients who need to have a radiograph, in contrast to film packages where a new package is used for every radiograph that is made. Therefore digital image receptors should be covered to prevent cross-contamination. Together with the stiffness of most of the digital receptors this causes a different way of handling of the digital image receptor compared to what was common with film. Also the applied radiation dose, per radiograph as well as in total, differs from what was common in film-based radiography.

Next, the image display is different from film. The digital image is displayed on a monitor screen in much greater dimensions than the film image that is read on a viewing box. Brightness, contrast and many other image characteristics can be manipulated and may affect diagnosis on digital radiographs, while contrast and density of a conventional radiograph is determined during the exposure and film processing procedure and cannot be corrected afterwards.

Also the computer based storage and retrieval of digital radiographs differs to a great extend from the manual storage and retrieval process of film radiographs.

AIM OF THE STUDY

It will be clear that digital radiography differs from film-based radiography. In some aspects digital radiography to a great extent seems a replacement of film-based radiography, in other aspects digital radiography demands a completely different approach of the diagnostic process.

Digital dental systems are in use in general dentistry for about two decades now. In those 20 years about 20 to 25% of the general practitioners adopted digital radiography in their clinics and the technique has grown from ‘experimental’ to fully accepted and reliable. In the next

10 to 20 years the vast majority of dental practitioners will switch to digital radiography

In this study we want to examine the parameters that affect the radiographic procedure in general dental practice when implementing digital radiography. Those parameters range from the image acquisition to the diagnostic outcome including the applied X-ray dose. Therefore the aim of this study is to identify the most important parameters that should be taken into account when implementing digital radiography in general dental practice and to investigate how they influence the radiation dose and the diagnostic performance of digital radiography in comparison with conventional film based imaging.

STUDY SELECTION

Chapter 2 is a review which describes the two digital techniques that are available for digital dental radiography: direct and indirect (or semi-direct) digital radiography. It emphasizes the comparison between digital imaging and film-based imaging in image acquisition as well as diagnostic efficacy.

A digital image can be enhanced by image processing to make relevant information more evident. Different diagnostic tasks might require different image enhancement procedures. Therefore the review of the literature on diagnostic efficacy of digital systems is subdivided in paragraphs dealing with the diagnosis of caries, the visibility of endodontic files, the detection of periapical lesions and the display of periodontal lesions. Apart from that subdivision a separate paragraph describes the general effects of image enhancement on diagnostic efficacy. Factors influencing X-ray dose when using digital or film-based radiography are described in the last paragraph of this review chapter.

Chapter 3 describes the use in general dental practice of the different techniques for image acquisition, digital as well as film-based. By means of a questionnaire filled out by more then 400 general practitioners much information was collected about the users themselves, the distribution of the different systems and use of aiming devices as well as the opinion of the general practitioners on user-friendliness of image acquisition, image processing and archiving, and diagnostics performed with digital or film-based radiography.

The radiation dose is another factor that is of great interest when changing to digital radiography. Since the introduction of digital dental radiography the dose reduction compared to film based radiography is strongly emphasized by notably manufacturers and resellers. Often manufactures in their advertisements stress the low dose that is needed to produce a radiograph with their digital system. However, this appears to be only one side of the story. In *Chapter 4*, also based on the questionnaire mentioned before, the number of radiographs that are taken is added to the 'dose story' as another parameter. This puts the potential dose reduction of digital radiography as compared to conventional film based radiography in a different perspective.

Chapter 5 continues the dose issue by studying the effect of the dose response (the 'dynamic range') of digital systems and film. Besides the number of radiographs that are taken also the applied radiation dose per exposure determines the total patient dose. In general, the image quality increases with increasing radiation dosage. This chapter describes the relation between the applied dose and dentists' satisfaction with the radiographic image. Subsequently the radiation range (dynamic range) per system is determined. The dynamic range of two digital technologies (direct and indirect) and film are compared and the effect of the dynamic range on patient dose is discussed.

Chapter 6 continues the topic of the dynamic range by putting the dynamic range in the perspective of the diagnostic performance for caries diagnosis. The International Commission on Radiological Protection (ICRP) in 2004 expressed concern about the influence of the dynamic range of digital systems on patient dose.[5] The commission is worried by the fact that digital systems have the potential to significantly increase patient dose. Namely, overexposure can occur without a noticeably adverse impact on image quality; it is even likely that the radiograph looks *nicer* (which does not automatically mean that the diagnostic performance is also better). To find out if a better subjective image quality corresponds with a higher diagnostic accuracy for caries detection, this chapter focuses on the relation between subjective image quality within the dynamic range of digital systems and the diagnostic accuracy of caries diagnosis.

Another issue regarding image quality, and therefore possibly affecting diagnostic performance, is the spatial resolution of the sensor. Comparable to the development of digital photo cameras, also digital X-ray sensors experienced an enormous increase in the number of pixels on the chip. *Chapter 7* compares the effect of the different spatial resolution settings on diagnostic performance with respect to caries diagnosis.

In *Chapter 8* (Discussion, General Conclusions and Summary) we will place the results of the preceding chapters in a broader context.

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Digital intraoral radiography in dentistry

Diagnostic efficacy and dose considerations

A review

INTRODUCTION

A radiographic image represents the X-ray shadow of patients' internal structures. In conventional film radiography the radiographic film detects, stores and displays the radiographic information. For a long time, radiographic film was the most important medium for the acquisition and archival of diagnostic images. However, since 1987 dental film is no longer unchallenged as the image receptor for intraoral radiography. At that time, the first *direct* digital system became available for dental practice as an alternative to conventional radiography.[1,2] Some years later, in 1994, the first *indirect* digital system became available commercially.

In digital radiography X-ray detectors and computers perform the acquisition, archival and display of the radiographic information. In ten years of time digital radiographic technology has matured and, nowadays, digital radiographic systems are gradually replacing radiographic film. In Western Europe 10-20% of the dental practitioners use digital radiographic imaging systems in their dental practice.[3,4]

Although film has been an inexpensive and reliable image receptor in dental radiography for a long time, the advantages of digital dental radiography over film include a lower radiation dose, a swift availability of radiographs, the possibility of image enhancement and no need for film processing chemicals. Many of those advantages are possibilities not found in conventional film-based imaging, which makes the comparison of digital imaging with film-based imaging complicated.

Many review articles and studies describe new systems, applications or possibilities without discussing the comparison to film-based radiography.[5-12]

The purpose of this article is to show typical characteristics of digital radiography and compare them to conventional imaging, and furthermore to discuss the additional possibilities of digital radiography.

First we will discuss the two technologies for digital image acquisition; secondly the image quality of the digital systems is discussed on the basis of the various diagnostic tasks. Image enhancement and dose aspects, will be brought up as well.

SYSTEMS

Analogue vs. Digital

Conventional radiography is based on the interaction of X-ray photons with electrons of silver bromide crystals in the film emulsion, production of a latent image, and subsequently chemical processing that transforms the latent image into a visible one.[13] The film-radiograph may have a continuous density distribution, limited only by the maximum and minimum values of density (black and white). Each optical density in between the minimum and maximum is related to the amount of light that can pass trough the film at a certain site. Based on the continuous density scale film-based images are called analogue images.

A digital image, on the other hand, consists of a matrix of cells having a range of various gray levels on the computer monitor. The X-ray intensity is translated into discrete values, called gray levels. The number of gray levels normally used is 256, which is equivalent to 8 bit per pixel (2^8=256). This range of gray levels is called the *contrast resolution*.

The contrast resolution of the human eye is usually between 50 and 100 gray levels, so the number of 256 gray levels in a digital image is sufficiently enough for the human visual system to simulate a continuous gray scale.

In digital images gray values are found only at well-defined spatial positions, called pixels (picture elements). The number of pixels per inch or centimeter defines the so-called *spatial resolution*. The more pixels are arranged in a matrix, the better the quality of the image that is captured. The limited number of pixels that can be grouped together restricts the digital spatial image resolution in solid-state systems. In phosphor plate systems the accuracy of the laser scanner and the scattering of laser light within the phosphor layer limit the spatial resolution.[14]

The smallest detectable object depends on the spatial resolution as well as the contrast resolution.[15]

In the literature the terminology to discriminate between several kinds of 'digital' systems is confusing. Most authors call digital sensor systems that are attached to the computer with a wire a direct system. However, phosphor plate systems are also called direct systems, because of the direct acquisition of the digital image. Other authors call phosphor plate systems ‘indirect systems’ because of the extra action that needs to be done to scan the plate in the laser scanner. Again others have found a compromise in the term ‘semi direct systems’. The digitization of a film radiograph to a digital image using a flatbed scanner or video camera is mostly called the truly ‘indirect system’.[16] Terminology that causes less confusion is ‘solid-state systems’ for sensor systems that are attached to the computer with a wire and on the other hand ‘phosphor plate systems’.

Solid-state systems

Solid-state systems include an electronic X-ray sensor, a digital interface card, and a computer with a screen monitor and software. Current systems are mostly based on personal computer (PC) technology and require a Pentium III processor (or higher), sufficient internal memory (at least 128 Mb), a SVGA graphics card and a high-resolution monitor (1024x768 pixels).[17]

Solid-state sensors are either a charge-coupled device (CCD) or a complementary metal oxide semiconductor active pixel sensor (CMOS-APS).

A CCD is made up of arrays of X-ray-sensitive or light-sensitive pixels. The size of one pixel is approximately 40 μm x 40 μm, some CCDs are even as small as 20 μm x 20 μm.[18] The pixels, in fact photoelectric cells, generate voltage in proportion to the amount of X-rays or light striking them. This charge is transferred (coupled) to a readout amplifier for image display. Intra-oral CCD-sensors fall into two categories: the fiber optically coupled sensors and the directly exposed sensors. Fiber optically coupled sensors use a scintillation (intensifying) screen coupled to a CCD. Light photons, that are the result of the interaction of X-rays with the screen, are transmitted by the fibers to the CCD. The directly exposed CCDs capture the image directly without the intermediate scintillation layer.[15]

In contrast to CCD sensors CMOS-APS sensors use an active pixel technology. This technology provides design integration what makes the sensor less expensive to manufacture and may improve the reliability and lifespan of the sensor.[13] However, CMOS-APS sensors have more fixed pattern noise and a smaller active area for image acquisiation.[17]

With respect to the physical performance of the different sensor systems, it was found that grey level values in images from solid-state systems decrease faster with increasing exposure than in images from phosphor plate systems, resulting in darker images and deterioration of the image caused by blooming effects. Noise increases with increased exposure for both solid-state and phosphor plate systems. Solid-state systems reach their highest contrast index at lower doses than the phosphor plate systems. Solid-state systems have better resolving power due to higher contrast and smaller pixel sizes than phosphor plate systems.[19]

Phosphor plate systems

Storage Phosphor Plate systems (SPP), also called Photostimulable Phosphor systems (PSP), temporarily store the radiation energy of the latent X-ray image on a sensitive plate. By stimulating the phosphor on the plate with a laser-beam in a readout-scanner, the energy stored on the plate is emitted as light. The intensity of the light in a given area is linearly proportional to the amount of X-ray energy that has been absorbed. The scanner measures the emitted light. The measurements are displayed on the monitor as a digital image. [14,20]

The phosphor plate is able to store the X-ray energy for many days; however, it is best to read them as soon as possible. In one day an exposed imaging plate, stored in a dark environment and enclosed in a protective bag, loses half of its stored energy.[21] After read-out flooding the plate with bright light erases any residual energy. The phosphor plates are reusable, and therefore should be enclosed in an infection control barrier before placement in the mouth of the patient. The image plates cannot be sterilized.

The image size and the fact that the plates are cordless, in contrast to solid-sate systems, make phosphor plate systems and conventional film very similar with respect to the manipulation of the plates in the mouth of the patient.

The pixel size of phosphor plate systems is depending on the focal spot of the laser-beam and the accuracy of the movement of the plate or laser-beam in the scanner. [21] The pixel size of the first Soredex Digora® phosphor plate system (Soredex-Orion Co., Helsinki, Finland) (white plates) is 70 µm.[22] The new version, the Digora FMX system produces an image of 628 x 466 pixels for the same active area, resulting in a pixel size of 64 µm.

The development of digital radiographic systems is still going on. Especially for solid-state systems this development is going rapidly. In the last two years, many manufactures have developed high-resolution sensors that are producing 12-bit data output, giving 1024 gray levels.

Since the development is going rapidly, it is important for researchers to clarify in scientific publications which system and which version of that system they used. Also the version of the software of the system should be mentioned. Unfortunately, at this moment many authors do not clearly describe the system used in their studies.[22, 23, 58]

DIAGNOSTIC EFFICACY

Cariology

Carious lesions have traditionally been detected by a clinical examination supplemented by radiography. The use of radiographs increases the number of lesions detected by clinical examination.[24] However, numerous studies have demonstrated the tendency for radiographic diagnosis to underestimate the severity of the lesions.[25-27]
New imaging modalities, such as digital radiography, should at least have an accuracy that is comparable with that of dental films.

A study of the first digital system for intraoral radiography (the Trophy RadioVisioGraphy) showed no statistically significant difference with conventional film and digitized radiographs for the detection of dentinal caries in occlusal surfaces of noncavitated extracted teeth.[28]

Meanwhile many more studies have shown that solid-state sensors (CCD as well as CMOS-APS) and most phosphor plate systems performed as well as E-speed film in diagnostic efficacy for proximal caries.[23, 29-33] Two studies investigating the CD-dent phosphor plate system, previously Digident (Orex, Yokneam, Israel), showed that this system is not as accurate as the other digital radiographic systems. Observers ranked the system inferior.[34, 35]

In most cases the exposure time for the digital radiographic systems was set to 10-50% of that of E-speed film. All studies mentioned were performed using a common dental tube potential (65 or 70 kVp). Research has shown that a variation of tube potential has a negligible effect on proximal caries diagnosis using X-ray film.[36] However, it has never been shown that this is also true for digital radiography. More research is needed.

In vivo research in caries radiodiagnosis is not regularly performed, mainly due to the difficulty of obtaining a 'gold standard'. Hintze & Wenzel found no significant difference in the diagnostic accuracy of film radiographs obtained both *in vivo* and *in vitro* of the same third molars for the detection of occlusal and approximal caries.[37] It was concluded that the results from good laboratory studies could be transferred to the clinical situation. However, an *in vivo* study by Versteeg *et al.* comparing the Digora phosphor plate system with E-speed film for the detection of proximal caries showed that the phosphor plate system underestimated caries depth in comparison with film-based images.[38]

For the Digora system Møystad *et al.* studied the accuracy of proximal caries detection using original and digitally enhanced storage phosphor images and E-speed film.[39] For both enamel and dentin lesions the enhanced images performed significantly better than the original digital radiographs and film. No significant difference was found between the original digital radiographs and film. Another study showed that a caries-specific enhancement procedure (the so-called Oslo enhancement filter) of storage phosphor images significantly improved the accuracy of caries depth assessment in the outer half of the enamel compared with E-speed film, and moreover, it reduced interobserver variability. For caries lesions penetrating beyond the outer half of the enamel no significant differences were found.[40]

In addition to the positive effect of image enhancement on diagnostic efficacy, also magnification seems to have a significant influence on observer performance in the detection of proximal caries.

However, there is an upper limit of about 15x magnification beyond which diagnostic accuracy may be reduced.[41, 42]

Endodontology

Manufacturers of digital radiographic systems, notably solid-state systems, advocate the use of their products particularly in determining root canal length during endodontic treatment. In those cases, the rapid image acquisition is the selling argument.

Several studies have been performed on the diagnostic efficacy of digital radiographic systems with respect to determining the length of the root canal or the visibility of endodontic files.[43-46] Those studies concluded that the digital systems used in the studies provided comparable results to conventional film-based radiography in determining the length of the root or root canal.

However, Shearer *et al.* were less satisfied with the performance of digital systems in determining root canal length. Three phosphor plate systems (Digora, CD-dent and DenOptix) (DenOptix, Dentsply-Gendex, Milan, Italy) and E-speed film were compared with respect to the imaging of root canals.[47] For this task a good low contrast distinction is a requisite. It was concluded that the length of the root canal is better visible on conventional film than on the three phosphor plate systems. In the opinion of the authors this might be of clinical relevance.

Another important diagnostic task in endodontic radiography is determining the length of the endodontic file in the root canal. In 1994, Sanderink et al compared five solid-state systems with Ektaspeed film on the visibility of endodontic files. It was concluded that the digital systems performed equally to film with the use of file size 15, but film outperformed the digital systems with the use of file size 10.[48] Also Versteeg *et al.* (1997) and Lozano *et al.* (2002) concluded from their studies that digital systems and conventional film are comparable with respect to the visibility of endodontic files when using file size 15 or higher.[49, 50] Vandre *et al.* studied six digital radiographic systems and film on the accuracy for endodontic measurement.[51] All digital systems gave greater mean measurement errors than film. However, three of the studied digital systems (Dexis, CDR and RVG-4) (Dexis, Provision Dental

Systems, Palo Alto, CA, USA), (CDR, Schick Industries, Long Island City, NY, USA), (RVG-4, Trophy Radiologie S.A., Croissy-Beaubourg, France) did not differ significantly from film. The other three digital systems (Digora, Sens-A-Ray and Visualix-2) (Sens-A-Ray, Dent-X, Regam Medical Systems, Sundsvall, Sweden), (Visualix, Dentsply, Milan, Italy) did differ significantly from film. Apparently, the researchers judged the differences as relatively small, because they concluded that digital systems closely approximate film in their accuracy when used for endodontic measurement. Cederberg *et al.* (1998) and Eikenberg and Vandre (2000) were even more enthusiastic about digital radiographic systems.[52, 53] They both concluded from their studies that measuring the distance between file tip and apical foramen was statistically significantly more accurate on digital radiographs than on film, although this was thought to be of no *clinical* benefit.

Periapical lesions

Several studies have evaluated the efficacy of digital radiographic systems in the detection of periapical lesions. Holtzmann *et al.* (1998) compared D-speed film, E-speed film and the Digora phosphor plate system with respect to the detection of periradicular pathosis.[54] Radiographs were made of 100 cadaver jaws, which subsequently were sectioned for histologic examination. The observer performance was compared with the true histologic findings. It was determined that D-speed film, E-speed film and the phosphor plate system were equivalent diagnostic imaging modalities with regard to the detection of periradicular bone resorption. Also Paurazas *et al.* (2000) compared three systems, E-speed film, a CCD system, and a CMOS-APS system.[55] She did not mention the make and type of the systems. Periapical lesions were created in the cortical and trabecular bone of 10 dried human mandibles. Lesion detection by seven observers occurred with significantly greater accuracy in cortical bone than in trabecular bone. Nevertheless, no differences were found in the detection of the lesions between film, CCD, and CMOS-APS systems. Kullendorff *et al.* studied the diagnostic accuracy of digital radiographs for the detection of periapical lesions too.[56] They also drew the conclusion that the quality of digital images is comparable to that of E-speed film for the detection of periapical bone lesions.

On the other hand, a study by Wallace *et al.* (2001) showed that conventional film-based radiography was better for the detection of periapical lesions.[57] The study compared Ektaspeed Plus film (Eastman Kodak, Rochester, NY, USA), the Digora phosphor plate system, and the Schick-CDR solid-state sensor. Lesions were simulated in the periapical areas of human mandibular sections and imaged using the three systems. Ektaspeed Plus film outperformed both digital systems in sensitivity and specificity for the detection of periapical lesions.

Periodontology

The diagnostic efficacy of digital imaging has also been explored with regard to periodontal lesions. Nair *et al.* evaluated the accuracy of alveolar crestal bone detection in a comparison of original and enhanced Sidexis digital images (Sirona Dental Systems GmbH, Bensheim, Germany) with Ektaspeed Plus film.[58] More than 100 proximal and furcal areas in the anterior and posterior areas of the mandible and maxilla of three human skull phantoms were imaged. Five observers assessed all images for the presence or absence of crestal bone loss. It was concluded that the Sidexis digital images were not significantly different from Ektaspeed Plus film for crestal bone evaluation.

Eikholz *et al.* compared linear measurements of interproximal bone loss on digitized radiographic images after application of different filters to the gold standard of intrasurgical measurements.[59] Neither the measurement of the distance from the cemento-enamel junction to the alveolar crest on the unchanged images nor assessments with any of the filters revealed significant differences from the gold standard. Therefore, it was concluded that all radiographic assessments on the digitized images came close to the intrasurgical gold standard.

The effect of image enhancement on diagnostic efficacy

Digital acquisition of radiographs enables digital image enhancement. In diagnostic imaging, the objective of image processing is to make relevant information more evident by creating images that are better suited for human visual perception.[60] The same image may be used for various diagnostic tasks by adjusting the image characteristics. For instance a radiograph should be lighter for detection of marginal bone loss, whereas caries detection requires a darker image with increased contrast. Smoothing reduces the image noise, at the expense of a decrease in resolution. High-pass spatial filtering (hardening) enhances edges thus returning a crisper image, but with more noise.[15] All systems for digital imaging offer one or more types of image enhancement methods, causing a great variety of techniques among all systems. This made Lehmann *et al.* conclude from their study that standardized terminology and increased functionality of image processing should be offered to the dental profession.[61]

A study by Borg (1999) has shown that the images of phosphor plate systems need some enhancement to improve the diagnostic performance.[19] This is because the resolving power of the phosphor plate systems improves when the images are enhanced. The software of phosphor plate systems usually applies the systems' default greyscale adjustment to the images to perform the needed enhancement. However, noise in phosphor plate images will increase to a certain extent when image enhancement is applied. When exposure increases noise decreases.

Several studies have shown that digital contrast enhancement and filtering may increase diagnostic accuracy.[39, 62] Svanaes *et al.* conducted a study on image enhancement of phosphor plate images.[40] As mentioned in the paragraph on cariology of this article, it was concluded that digital image enhancement of storage phosphor images significantly improved the accuracy of caries depth assessment in the outer half of the enamel compared to Ektaspeed film. Also Shrout *et al.* concluded from their study on the effect of image enhancement that it improved the validity of caries assessment.[63]

However, the results of many studies on image enhancement are rather divided. Even deterioration of diagnostic accuracy by digital image enhancement has been reported.[64] Kullendorff *et al.* (1997) performed a clinical study in which a Visualix/VIXA solid-state sensor was compared with Ektaspeed film for the detection of periapical lesions. Conventional periapical radiographs as well as digital periapical radiographs were taken of 50 patients. Observer performance was assessed of conventional radiography and of digital radiography; the latter with and without image processing and ROC-analysis was applied. A_z-values showed no significant differences between conventional radiographs and original digital images.

The enhanced digital images performed significantly worse for the detection of periapical lesions. Also Farman *et al.* did a clinical study on the accuracy of the assessment of intraosseous lesion dimensions.[65] Ektaspeed Plus radiographs and the Visualix-2 solid-state system in unenhanced, contrast-stretched and equalized modes were compared. When image equalization was applied, the measurements were closest to the "gold standard". The contrast-stretched and unenhanced measurements were less accurate; conventional film was consistently the least accurate.

Kullendorff *et al.* made a comparison between original digital images and images processed with different enhancement procedures.[66] The results show that basic image processing, which is altering of contrast and brightness, are after all the most effective. More complicated processing procedures have less effect on the diagnostic accuracy. It was concluded that image processing of digital images of high quality had a limited effect on the diagnostic accuracy.

Wolf *et al.* performed a study on the efficacy of image enhancement in periodontology.[67] The aim was to assess the reproducibility and validity of linear measurements of interproximal bone loss on digitized radiographic images after application of different filters. It was concluded that the chosen filters failed to result in statistically significantly more reproducible or valid measurements when compared to the digitized but unchanged images. Nair *et al.* and Eickholz *et al.* drew the same conclusion from their studies on the accuracy of alveolar crest bone detection.[58, 59]

We conclude that due to the subjectivity and task-dependence of image enhancement it can be expected that general use of such enhancement techniques may not lead to improvement of diagnostic efficacy. Only for caries diagnostics most studies concluded that enhancement improves the detection of small lesions. In general, the optimal image enhancement technique for a given diagnostic task is a function of the digital radiographic system used, the diagnostic task, characteristics of the display medium, and the human observer.[68]

SUBJECTIVE IMAGE QUALITY

Subjective opinions on the image quality of digital radiographs by experienced dental radiologists and dentists are another approach to evaluate the utility of the digital systems tested. Already in 1977, Thornbury *et al.* proposed a methodology for comparison of quality of radiologic images based on radiologists' subjective judgements.[69] Using this methodology, Vucich suggested subjective evaluation of the degree to which pre-defined anatomical landmarks are clearly visualised.[70] Kundel suggested a similar approach to define image quality because of his observation that the role of the observer performance in the evaluation of diagnostic image quality has been underemphasized compared with the technical aspects.[71] It is assumed that such a subjective evaluation will also include the effects of the physical parameters of the imaging system influencing the diagnostically important aspects of image quality.[72]

An advantage of this approach is that the image quality of a radiograph can be evaluated for a variety of diagnostic tasks. So a situation is created that is comparable to the general dental practice.

Recently, in two studies several digital radiographic systems were compared using subjective image quality. Kitagawa *et al.* compared three intra-oral phosphor plate systems, the Digora system, the DenOptix system with two different types of phosphor plates, and the DigiDent (CD-Dent) system.[34] It was concluded that DenOptix combined with BAS300 phosphor plates (Fuji Photo Film Co., Tokyo, Japan) gave the best overall image quality, whereas the Digora images were considered to be the best for demonstrating gingival soft tissues.

Borg *et al.* compared four solid-state systems and two phosphor plate systems.[72] It was concluded that the Schick-CDR CCD and APS solid-state sensors had the best image quality, but also the narrowest exposure range. Both phosphor plate systems (Digora and DenOptix) provided a clinically acceptable image quality over a wide exposure range, and both Visualix systems had the lowest image quality. In addition, this study as well concluded that image enhancement did not generally improve image quality.

Farman *et al.* compared the subjective image quality of the Visualix-2 solid-state system to Ektaspeed Plus film in an in vivo study.[65] The subjective preference of the observers placed enhanced Visualix-2 images above film radiographs, but unenhanced Visualix-2 images were rated worse than film radiographs.

The diagnostic efficacy of digital radiographic systems as determined in laboratory studies and a few clinical studies seems to be clinically acceptable and useful. Therefore, digital radiographs can be used diagnostically without compromising the interests of the patient, and subsequently used for further studies on the diagnostic performance of these systems. However, histological validation of the findings is usually not possible in clinical studies. Consequently, another manner of comparing the images should be found. The choice of the validation method is crucial in this respect. Hintze and Wenzel concluded that the diagnostic efficacy as a measurement of system performance was strongly influenced by the validation method.[73]

From another study on the comparison of microscopy and radiography as gold standards in radiographic caries diagnosis, Hintze and Wenzel claimed that results obtained using observers' scores from the radiographs, as validation for the presence of caries, might mislead the clinician.[74]

When radiographic validation misleads the clinician and histological validation is not possible in an in vivo study, subjective image quality assessment seems to be a useful method to compare digital radiographic systems mutually and with film in a clinical setting.

DOSE CONSIDERATIONS

Radiation safety is an important issue in dental radiography. The desired amount of information must be obtained with the smallest possible amount of radiation. The dose reduction obtained by digital radiography as compared with film-based radiography has been emphasized since the introduction of digital imaging in dental radiography in the 1980s. It is questionable, however, if the dose reduction is as large as has been suggested by manufacturers and some users. At first, the dose should be compared with E-speed or even F-speed film. The use of D-speed film as the reference as used in many publications overrates the dose reduction.[46]

Yet, compared to E-speed film in laboratory conditions, digital intraoral radiography requires a dose per exposure that is generally lower than that for conventional film-based radiography.[14, 31, 62, 75-78] A survey on the use of digital radiography in general dental practice in Norway showed that the mean reduction in exposure time was 55%.[79] The expectation that users with small size digital sensors would collimate their radiation field could not be confirmed.

Moreover, the patient dose is determined not only by the amount of radiation per exposure, but also by the number of radiographs taken. A recent study shows that the total number of radiographs taken by dentists using digital radiography was significantly larger than the number of radiographs taken by film-users.[80] The number of radiographs taken by dentists using solid-state systems compared to film-users increased by nearly 50%. Phosphor plate users took 32% more radiographs. Several factors do explain this increase. According to the answers of the dentists in the survey, better diagnostics was the main reason when taking more radiographs. However, a study by Versteeg *et al.* also showed that positioning errors occurred more often in digital radiography than in film-based radiography.[81] Because of the stiffness of the digital sensors the positioning in the mouth of the patient is significantly more difficult than positioning film, and more uncomfortable for the patient.[3, 82] This also is an important factor of extra radiographs to be taken. Another reason for retakes might be the relatively narrow dynamic range of solid-state systems. Blooming effects will deteriorate images from solid-state systems at lower doses than burn-out effects deteriorated conventional radiographs or images from a phosphor plate system.[19, 75]

CONCLUSIONS

Digital intra-oral radiography is a well-accepted diagnostic tool in dental practice. However, some of the claims made by manufacturers of digital systems, are not valid to their full extent. For instance, the dose reduction per exposure is real, but it is still to be determined what the actual dose reduction is because of the fact that dentists tend to make more radiographs when using a digital system. For many dentists, digital radiography is a new technology. This requires additional training before the quality of the imaging procedure in hands of the dentist and the members of his team will match their experience gained in conventional radiography.

Other aspects, such as image enhancement and task specific image optimization, still need further research before the patient can fully benefit from this added value of digital systems.

It is nevertheless clear from many studies that the diagnostic performance of digital radiography is at least comparable to or even better than that of conventional radiography. Digital radiography is a helpful tool in clinical practice.

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3

A comparison of digital and film radiography

A questionnaire study of Dutch dental practices

ABSTRACT

Objectives:
The purpose of this study was to assess the experiences of general dental practitioners (GDPs) with solid-state and storage phosphor digital sensors compared to film.
Methods:
In a mail survey 578 questionnaires were sent to Dutch GDPs who were users of digital X-ray detectors and film. The questionnaire requested demographic data, information about the digital system used and the user-friendliness of the X-ray detector system. In the analysis of the data these variables were related to the type of system used and also to the demographic data. The data were analysed using descriptive statistics, variance-analysis (One-Way ANOVA) and nonparametric tests (Kruskal–Wallis, Mann–Whitney and Wilcoxon) (SPSS 9.0).
Results:
Four hundred and twenty-four questionnaires were returned (overall response rate
73%). The user-friendliness of the handling of the different systems before exposing the radiograph is better for conventional film, whereas the handling after exposing the radiograph favoured the digital X-ray detector systems.
Conclusions:
The user-friendliness was best for film pre-exposure and digital sensors post-exposure.

INTRODUCTION

Dental digital radiography sensors can be divided into storage phosphor plates (SPP), also called photostimulable phosphor plates (PSP), and silicon devices such as charge coupled devices (CCD) or complementary metal oxide semiconductors (CMOS).[1-3]
In this paper CCD and CMOS sensors will be referred to as solid-state detectors. A phosphor plate stores the latent image in the phosphor crystals, which is read out by a laser scanner. The plates are similar in size and thickness to conventional dental X-ray film and are exposed in a similar manner. Solid-state detectors are bulkier and attached to a cable with a different exposure protocol compared to film. Currently about 12% of the 7000 total of Dutch general dental practitioners (GDPs) use a digital X-ray detector.

In several studies the advantages of digital radiography have been compared to conventional film.[4-9] Lower radiation dose, reduction of time between exposure and image display, image enhancement and magnification are examples of potential advantages over film. However, most studies evaluated the performance of the systems in laboratory conditions. Recently two studies have been published about digital radiography in dental practice.[10,11]

The aim of this study was to compare the experiences of GDPs using either SPP or solid-state or film detectors in the dental office. The objectives were to obtain information about the user-friendliness of the three x-ray detector systems, and how well they can be operated in a clinical environment.

MATERIALS AND METHODS

A questionnaire was designed concerning demographic data, type of digital system if used, the user-friendliness of the detector system, including the use of aiming devices. Some questions were matched to the detector used, such as ‘film’, ‘phosphor plate’, ‘CCD-sensor’, ‘processing’ and ‘scanning’. Some specific questions were: What is the age and gender of the respondent? Why do GDP film users choose not to purchase a digital system? How user-friendly is the current detector system? What size is the X-ray detector (CCD-sensor, phosphor plate or film)? Are aiming devices used when taking X-rays?

Dentist selection and response rates

The Dutch Dental Association and most dental suppliers provided lists of GDP's addresses. The Dental Association addresses were randomly drawn from a database of all Dutch dentists. One hundred and seventy-three questionnaires were sent out to GDPs using solid-state systems (Gendex Visualix, Sidexis, Schick CDR, Vistaray, Dexis and Dixi) and 300 questionnaires to GDPs using SPP-systems (Digora, Denoptix and Digident). These respondents comprised the ‘digital group’. All dentists on the address lists of the suppliers received a questionnaire as well as a control group of 105 GDPs using conventional film drawn from the Dutch database. There was some overlap between the addresses drawn randomly from the Dental Association database and the lists from the equipment suppliers. Those dentists were categorized in the ‘digital’ group. In total, 578 questionnaires were sent out.

To improve the response rate of the film-users telephone calls were made in advance to this group. As a result 105 GDPs, out of the 150 that were approached, agreed to fill out the questionnaire and 76 of the 105 actually responded (72%). Similarly the SPP-system users were approached by telephone before the questionnaire was sent out. However, due to the late provision by the suppliers of a list of the solid-state system users, no advance telephone calls were made to this group.

User friendliness

All GDPs were asked about their experience with handling their system for radiography. A 5-point scale was used (1-very difficult, 2-difficult, 3-neutral not easy and not difficult, 4-easy and 5-very easy). Specific areas requested were: preparing the detector before placing it in the mouth; positioning the detector in the molar-region; positioning the detector in the anterior region; positioning the detector in children's mouths; processing the film and scanning the phosphor plate; diagnostics; archiving; system maintenance.

'Preparing the detector' means the various actions required with regard to the hardware and software (i.e. initiating the software, wrapping the sensor or phosphor plate in a cross-infection barrier, placing the detector in an aiming-device).
'Diagnostics' refers to the ease of viewing images from their original size, the possibility to enlarge and enhance the images, for both digital and film images. For each group (solid-state-sensor / phosphor plate / film) the mean and standard deviation of the individual responses were computed and a Mann-Whitney-test for differences between each groups was performed. Higher mean values indicate that a particular aspect of the handling is easier, whereas lower mean values indicate more difficulty.

Another comparison was made asking the users of digital systems how they experience their system relative to film. A 5-point scale was used (-2 much more difficult than film, -1 more difficult than film, 0 neutral, 1 easier than film and 2 much easier than film).

Intention to purchase and Satisfaction
The users of film were asked if they had plans to purchase a system for digital radiography and if not why not. Digital system users were asked what kind of system they would buy next time.
Detector size and Use of aiming devices
All participants were asked to measure the size of their X-ray detector(s) (solid-state-sensor, phosphor plate or film) in millimeters. The measured values of the sensors were rounded off to the nearest 'standard' film size. Respondents were asked to report their use of beam aiming devices as 'always', 'often', 'sometimes' or 'never'.
Statistical analyses were performed using SPSS 9.0. Differences were considered statistically significant when $P<0.05$.

RESULTS

The results are reported in percentages that have been rounded of to the nearest percent. Some respondents did not answer all the questions; in those cases only the usable responses for each particular question were used for the calculation of the percentages.

Response rates

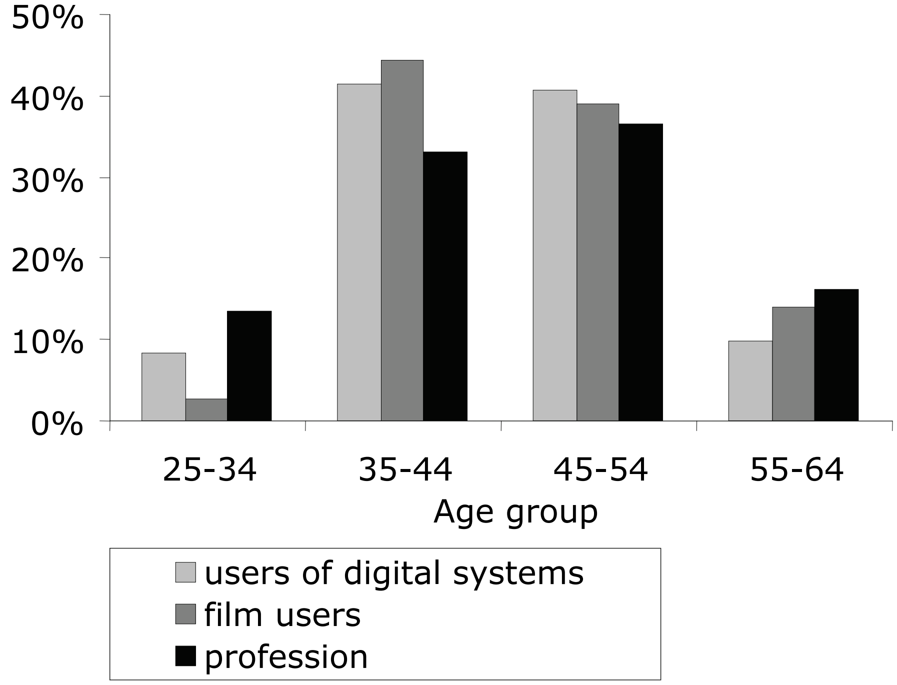
Five hundred and seventy-eight questionnaires were sent out and 424 returned with an overall response rate of 73% (Table 1). There were a few GDPs using both phosphor plate system and solid-state-system but because the number was very small, a reliable statistical analysis was not possible.

Table 1. Mailed questionnaires and percentage returned.

	Mailed	***Returned***	*Response rate*	***Percentage in survey***
Film	105	76	72 %	18 %
Phosphor plate	300	235	78 %	55 %
Solid-state	173	113	65 %	27 %
TOTAL	**578**	**424**	**73 %**	100 %

The last column shows the percentage of respondents in the survey for each of the imaging systems

Figure 1. The percentage of responding GDPs (for film users and users of a digital system) and the percentage of the whole population of Dutch dentists, divided into four age groups.



Demographics

Figure 1 gives an overview of the age distribution of the GDPs participating in this study and the age distribution as provided by the Dutch Dental Association. According to the Dental Association, 14% of the Dutch dentists are younger than 35 years of age, 33% are between 35 and 45, 37% are between 45 and 55, and 16% are older than 55 years of age (data from 1-1-2001).

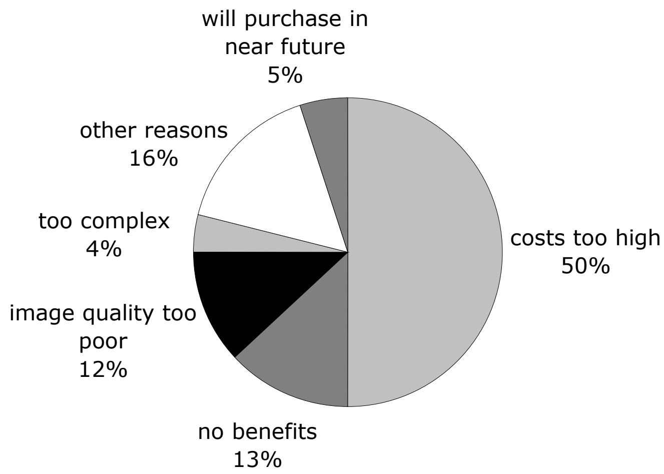
In our study, there are significantly more respondents in the age group 35-45 (42%, $P<0.001$), and fewer respondents in the age groups 25-35 (7%, $P<0.001$) and 55-65 (11%, $P=0.003$). These differences were found in the film user group and in the digital detector users. No statistically significant differences in response rate were found between the users of film and the users of digital systems and between the phosphor plate system users and the solid-state system users. According to the Dutch Dental Association, 22% of the Dutch dentists are female. The percentage in our group of film users was similar to this percentage. In the group of users of a digital X-ray detector system it was much lower (4%).

Intention to purchase a digital system

Seventy-seven per cent of the film users in the survey expected to implement digital radiography in their dental practice at some point in the future. Five percent of the film users are willing to purchase a digital imaging system in the near future (1 or 2 years).

These GDPs were also asked why they had not yet purchased a system for digital radiography. The largest group of 50% said because the 'costs were too high' (Figure 2, next page). Sixteen per cent of respondents were in the 'other reasons' group citing reasons such as the complexity of the software and hardware (4%) and retirement approaching in a couple of years (2%).

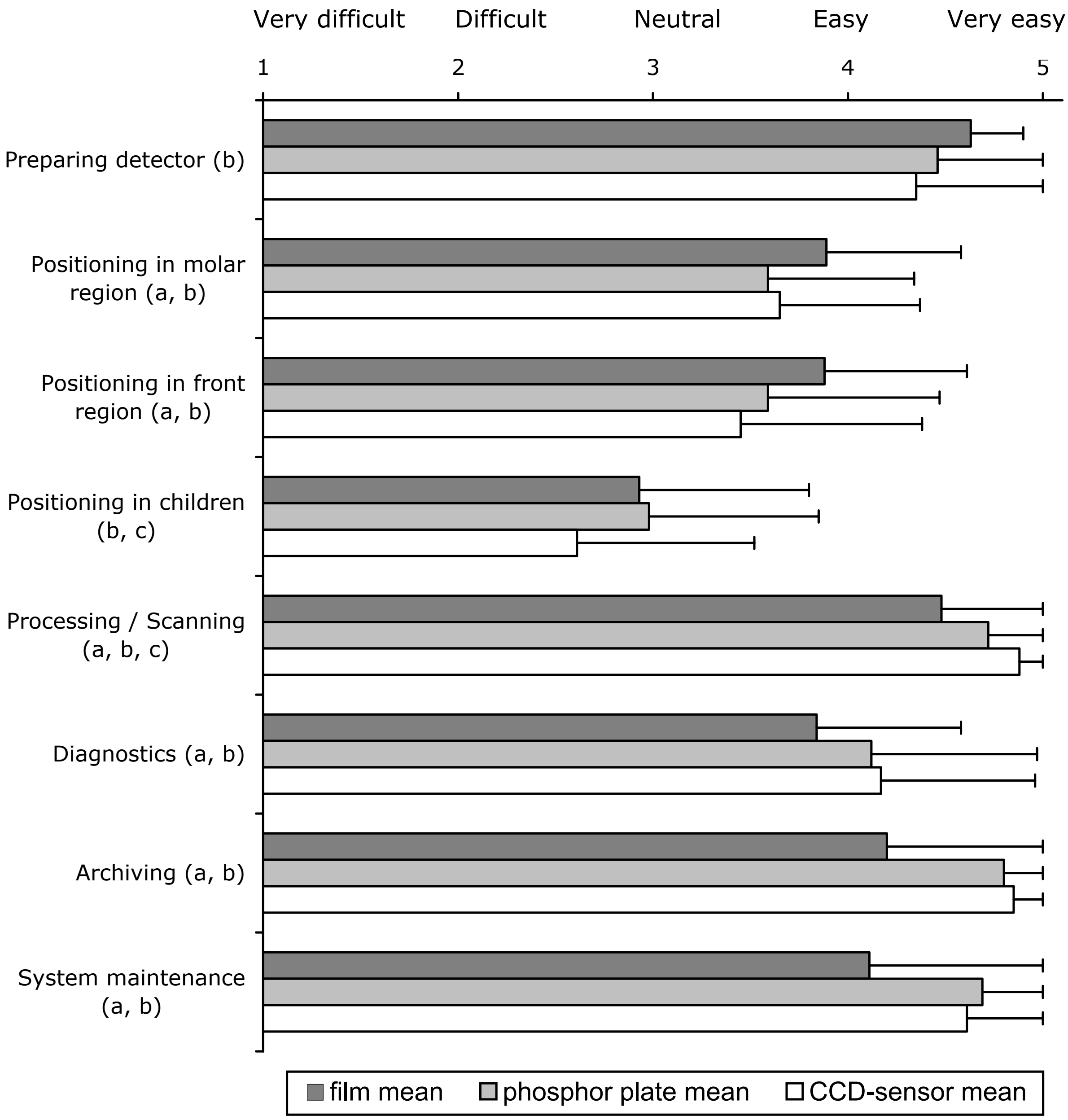
Figure 2. Reasons given by GDPs for not having a digital radiography system.



User friendliness

Figure 3 (next page) shows that the user-friendliness of conventional film and solid-state systems differed significantly in all aspects. Preparing the solid-state-sensor before placing it in the mouth is significantly more difficult (P=0.025) than preparing film. Positioning of the sensor in the mouth of the patient appears to be more difficult than positioning film (molar region P=0.021 and anterior region P=0.003, and positioning in children P=0.036). However, solid-state systems score a higher mean value for 'processing/scanning' (P<0.001), 'diagnostics' (P=0.003), 'archiving' (P<0.001) and 'system maintenance' (P<0.001). On these aspects the handling of the solid-state system according to the users of such a system is easier than the handling of film according to film-users. Comparing the user-friendliness of conventional film with phosphor plates three aspects differ significantly. The phosphor plate users scored a higher mean value on the same aspects as solid-state system users did compared to film users. Scanning (P=0.009), diagnostics (P=0.004), archiving (P<0.001) and system maintenance (P<0.001) were easier for phosphor plate than for film users. For 'preparing the plate / film' and 'positioning in children' no statistical differences were found between phosphor plate users and film users. The positioning of phosphor plates in the molar (P=0.001) and anterior region (P=0.018) was found statistically more difficult than positioning film.

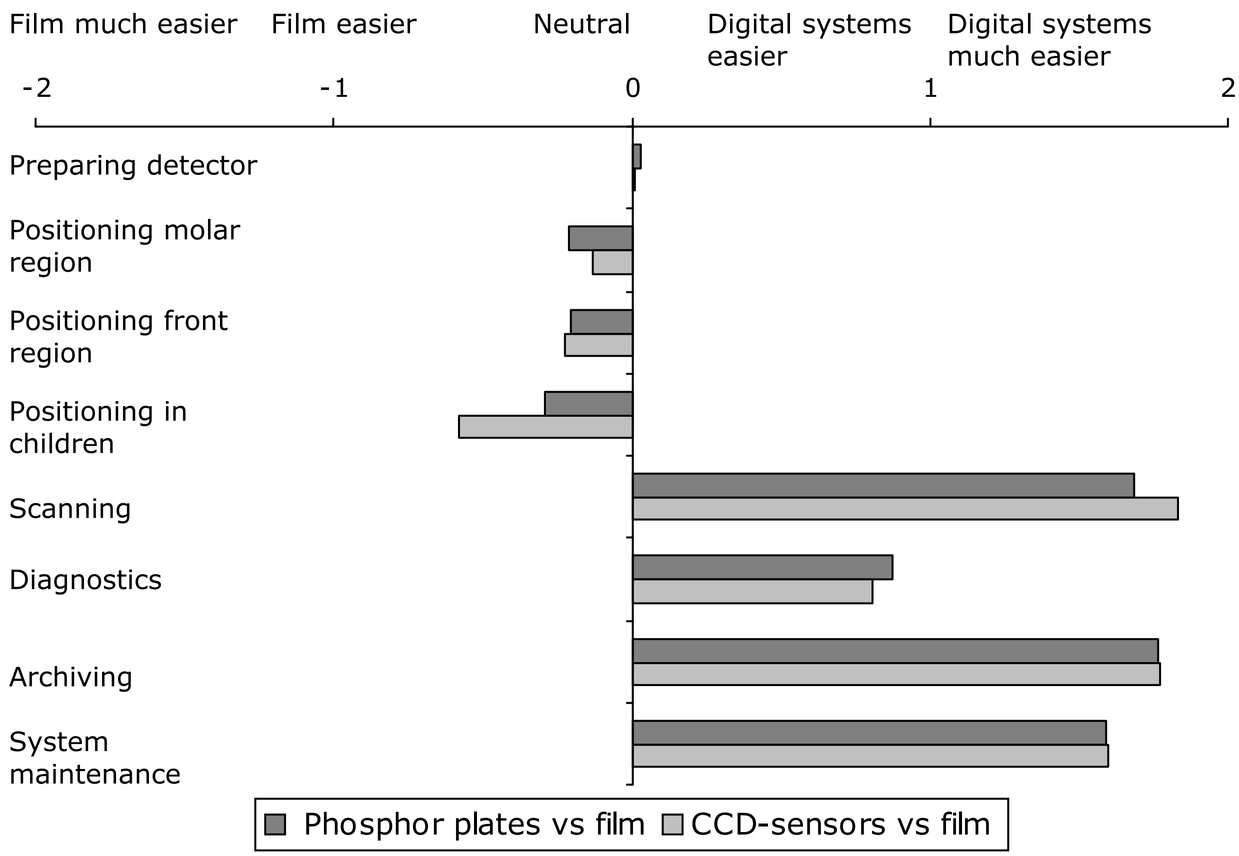
Figure 3. Comparison of the user-friendliness of various tasks of X-ray detector systems. The significant differences are marked with an (a),(b) or (c) behind the description of the tasks: a=between film and phosphor plate systems, b=between film and solid-state systems, c=between phosphor plate systems and solid-state systems.



For solid-state sensors and phosphor plates, a statistically significant difference was found for 'scanning' and the positioning in children's mouths. The 'scanning' aspect was easier for the solid-state system users than for the phosphor plate users (P=0.002), whereas the positioning in a child's mouth was easier (P=0.001) for users of a phosphor plate system than a solid-state system. No significant differences were found on the other aspects.

When users of a digital system were asked about their system relative to film, two significant differences were found between solid-state systems and phosphor plate systems: positioning in a child's mouth and the scanning (Figure 4).

Figure 4. Comparison of user-friendliness of both digital techniques relative to film.

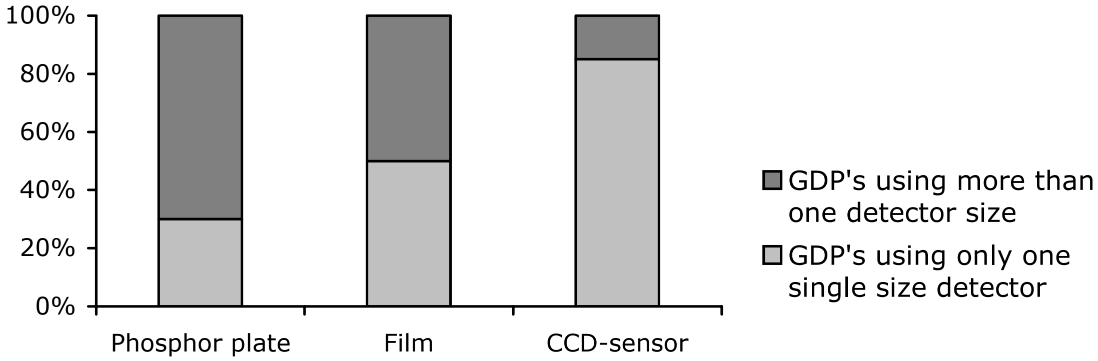


Solid-state system users reported positioning of the detector in a child significantly more difficult than phosphor plate users. However, it was the reverse for image acquisition compared to processing film.
Users of a digital system reported the positioning of the detector as more difficult than positioning film but easier for 'scanning', 'diagnosing', 'archiving' and 'system maintenance'.

Satisfaction
The majority of phosphor plate users (96%) as well as solid-state users (95%) would buy the same digital imaging system again. In both groups 2% would return to film.

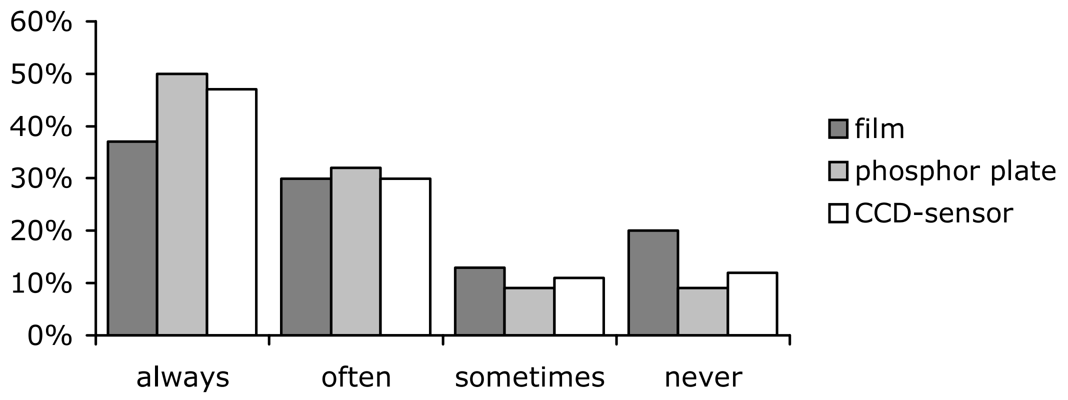
Image detector size
Almost 70% of dentists with SPP use more than one plate size (87% use sizes 0 and 2, 3% use sizes 0, 1 and 2), whereas 85% of respondents with a solid-state system use only one sensor size (Figure 5). Film users take a mid-position: 50% use two or more film sizes; the other half use only one size (> 89% size 2). In 96% of the cases SPP users with only one plate use a size 2 plate. GDPs with more than one solid-state sensor, in most cases (71 %) are using sensor sizes comparable to size 0 and size 2. GDPs with only one solid-state sensor use size 2 in 59% of the cases, a sensor size 1 and size 0 in both 20% of the cases.

Figure 5. Percentage GDPs using one size or more than one size film, solid-state sensor or phosphor plate.



Aiming devices
The frequency of aiming device use with the three different detector groups is categorized into four groups, ranging from 'always', 'often', 'sometimes' to 'never' (Figure 6). There is little difference in the 'often' and 'sometimes' categories. Digital detector users have more 'always' than film users but this did not reach a significant difference. Significantly more film users than SPP users 'never' use aiming devices. No significant difference was found between film users and solid-state system users.

Figure 6. The frequency of use of aiming devices for each of the imaging systems



DISCUSSION AND CONCLUSION

Response rates
The overall response rate in this study was 73% with most respondents receiving a preparatory telephone call. The personal approach will have had a positive effect on the response rate. This idea is supported by the fact that the response rate of the group of respondents that was not called in advance was lower. Film users might be less interested in a survey about digital radiography. The response rate for this group, nevertheless, was rather high (72%).

An interesting issue is the question if no-response has effects on the results of the survey. Various research reports indicate that there is no significant amount of no-response bias in a well-educated, homogeneous population.[12] Wallace[13] found in his study that there was no significant no-response bias when the sampled group was sufficiently homogeneous; that means similar in education, income, and interest. It is reasonable to assume that dentists have sufficiently similar education, income, and interest to be considered as a homogeneous group.[12] The literature reports that response rates of dentists to once-mailed surveys are 50-70%.[14 - 17]

Demographics

The youngest and oldest age groups had a lower response rate than could be expected based on the age distribution of the profession. The lower response rate in the oldest age group may be caused by the lower priority of digital radiography in this group because of approaching retirement. Most of the GDPs of the youngest age group have recently started their own dental office and therefore have large investments.

The interest in digital dental radiography by the age group 35-44 could be explained by the fact that these GDPs may have had their own dental office for 10 to 20 years and may be able to buy more equipment. These GDPs may also be more skilled in the use of computers than the GDPs of the oldest age group. Seventy-seven per cent of the film users expected to implement digital radiography in the future. This is surprisingly high since in the Netherlands there are no differences in insurance reimbursement rates for digital or film radiographs, yet the digital equipment costs could be a disincentive for change.

User-friendliness

Many significant differences in user-friendliness were found between digital X-ray detector systems and conventional film, and between the two digital systems. Preparing the solid-state sensor before placing it in the mouth is significantly more difficult than preparing film. Actions, such as packing the solid-state sensor in a hygiene-sheath or starting a computer program are not necessary when using conventional film. Although there was no significant difference between solid-state and SPP users for ‘preparation’ this may be explained by the possible packing of several SPPs at the beginning of the day prior to exposures. Perhaps packing a solid-state sensor is more difficult than packing a phosphor plate because of the attached cable and the shape of the sheath.

The survey reported that positioning digital detectors in the mouth is significantly more difficult than positioning film possibly because solid-state sensors are thick, stiff and attached to a cable. The Digora plates are also stiff and perhaps these respondents chose positioning to be ‘difficult.’

Most of the GDPs with a solid-state system use only a size 2 detector size which could be difficult to position in the anterior region, especially for small mouths and children. However, no significant difference was found between positioning film and SPP plates in children possibly due to SPP users having a small plate size available.

The survey found that digital systems were more user-friendly than film for handling of images after the patient exposure probably due to easier image processing and storage without the need for chemicals.

When users of a digital system compared their system with film, the solid-state users reported more difficulties positioning the sensor in children than SPP users probably related to available detector sizes.

Satisfaction

Almost all users of digital X-ray systems seemed pleased with their system because they indicated that they will buy the same system again. We did not investigate why dentists had opted for either a solid-state system or an SPP system.

Image detector size

Eighty-five per cent of the solid-state system users had only one sensor probably due to the high costs of sensors. A higher percentage of SPP users than film users had more than one detector size since systems are supplied with different plate sizes.

Comparison to a Norwegian study

Although the design of this study differs from a recent study by A Wenzel and A Møystad[10,11] who sent the ‘Norwegian’ questionnaire to all dental practitioners whereas our survey was sent to all users of digital radiography and a relatively small control group of film-users, some interesting parallels can be drawn. The percentage of dental practitioners using digital radiography appears to be comparable in both countries. Both studies showed that the price of the digital radiography is a major reason for film users for not purchasing such a system. This has also been reported elsewhere.[18]

The percentages of dentists using a phosphor plate system or a solid-state system are comparable in both countries. Two-thirds work with an SPP system and one-third with a solid-state system. Similar to our study the Norwegian study found more solid-state sensor than SPP users had difficulties with receptor positioning.

In conclusion, this survey indicates that dentists consider the user-friendliness of film to be better than digital systems *before* X-ray exposure but the reverse *after* exposure. Almost all the digital users preferred to continue with their system rather than return to film and many GDP film users are thinking of purchasing a digital X-ray detector system in the future.

ACKNOWLEDGEMENTS

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4

Does digital radiography increase the number of intraoral radiographs?

A questionnaire study of Dutch dental practices

ABSTRACT

Objectives:
To compare the number of radiographs taken in general dental practices equipped with digital radiography *vs* conventional film-based radiography and to determine the reasons for any difference in numbers.
Methods:
In a mail survey, 473 questionnaires were sent to Dutch General Dental Practitioners (GDPs) using digital radiography and 105 questionnaires were sent to GDPs using film. The questionnaire concerned the number of intraoral radiographs taken in the dental practice, as well as possible reasons to take more or fewer radiographs after conversion to digital radiography.
Results:
The response rate was 73%. Users of a phosphor plate system on average take 42.8 radiographs per week and solid-state system users take 48.4 radiographs, whereas film users take on average only 32.5 radiographs per week. The needs for more certainty about the planned or ongoing treatment as well as better diagnostics were the most important reasons for taking more radiographs.
Conclusions:
It seems that GDPs using a system for digital radiography are more inclined to take radiographs than dentists taking conventional radiographs. Although digital intraoral radiography requires 50–80% less radiation per exposure than film, it is likely that the effective dose reduction after converting from conventional to digital radiography is less than 25% owing to the greater numbers of radiographs taken.

INTRODUCTION

Radiation safety is an important issue in dental radiography. The desired amount of information must be obtained with the smallest possible amount of radiation. The dose per exposure is generally lower in digital intraoral radiography than in conventional film-based radiography.[1–9]

A large scale study on the use of digital radiography in general dental practice in Norway showed that on average the exposure time was reduced to about half of that for film.[10] In a previous study, we found that Dutch General Dental Practitioners (GDPs) experience more difficulties in positioning the detector of digital systems than film packets.[11] Together with the smaller sensitive area of most intraoral solid-state sensors (charged coupled device (CCD) and complementary metal oxide silicon (CMOS) sensors), this may result in a greater number of exposures for the same diagnostic task, thus increasing the dose to the patient. The expectation that users with small sized sensors would collimate their radiation field could not be affirmed in the above mentioned Norwegian study. There is no reason to assume that Dutch GDPs are different from their Norwegian colleagues and collimate their radiation field when using small digital sensors. All these factors raise the question of whether the dose to the patient in a clinical environment using digital systems is really smaller than the dose resulting from conventional film-based radiography, as claimed by manufacturers of digital systems.

The aims of this study were (1) to compare the number of radiographs taken in 'digital' and in 'film-based' general dental practices and (2) to determine whether a greater or lesser number of radiographs was taken after the conversion to digital radiography and what the reasons were for any change in number.

MATERIALS AND METHODS

Data regarding the numbers of radiographs taken by GDPs were collected using a questionnaire. GDPs using digital radiography and a control group using conventional film received a questionnaire. In total 578 questionnaires were sent out; 473 questionnaires were sent to GDPs using digital radiography (173 of these were using a solid-state system and 300 were using a storage phosphor plate system) and 105 questionnaires were sent to the control group using film. This resulted in three experimental groups: a solid-state group, a phosphor plate group and a control group.

The questionnaire and the method of analysis have been described more extensively in a previous study.[11] The questionnaire concerned the number of radiographs taken before and after digital radiography was introduced in the dental practice.

First, we asked the GDPs (both those using film and those using a digital system) how many radiographs they took per year. Because of the difficulty for GDPs to assess exactly the number of radiographs taken per year, they were asked to count the number of radiographs taken during 1 week. Related to that question, we asked the GDPs who were using a digital system whether they thought they were taking more, as many or fewer radiographs than before the conversion to digital radiography. Both questions made a distinction between bitewing radiographs and periapical radiographs.

Second, the threshold of taking and re-taking a radiograph was assessed by asking whether GDPs did or did not agree with the statement: "With digital radiography I decide more easily to take a radiograph than when I used conventional film." A similar statement was used with respect to repeat radiographs.

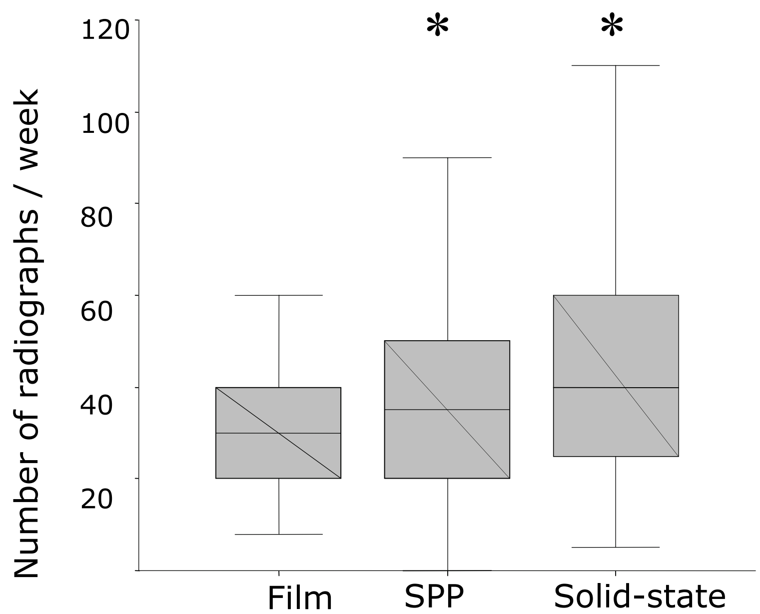
We also asked what reasons GDPs could have for taking a greater or lesser number of radiographs after as compared with before the conversion to digital radiography.

Statistical analyses were performed using descriptive statistics and non-parametric tests (Kruskal–Wallis, Mann–Whitney and X^2) of SPSS 9.0 (SPSS Inc., Chicago, IL). Differences were considered statistically significant when $P<0.05$. Where appropriate, a distinction is made between solid-state systems and storage phosphor plate systems in analysis of the data.

RESULTS

The total number of radiographs taken by GDPs using digital radiography was significantly higher than the number of radiographs taken by film users (P=0.003). This difference was found when comparing phosphor plate systems with film (P=0.023) as well as when comparing solid-state systems with film (P=0.001). No significant difference was found between the numbers of radiographs taken with the two digital systems (phosphor plate system and solid-state system).

Figure 1. Number of radiographs taken per week. *Statistical significance from film-users. SPP = Storage Phosphor Plate



The number of *bitewing* radiographs taken by GDPs using a solid-state system was higher than the number of bitewings taken by GDPs using film, but this difference was not significant (P=0.083). Also, no statistically significant differences were found between phosphor plate systems and film or between solid-state systems and phosphor plate systems (Figure 2).

Figure 2. Number of bitewing radiographs taken per week
SPP = Storage Phosphor Plate

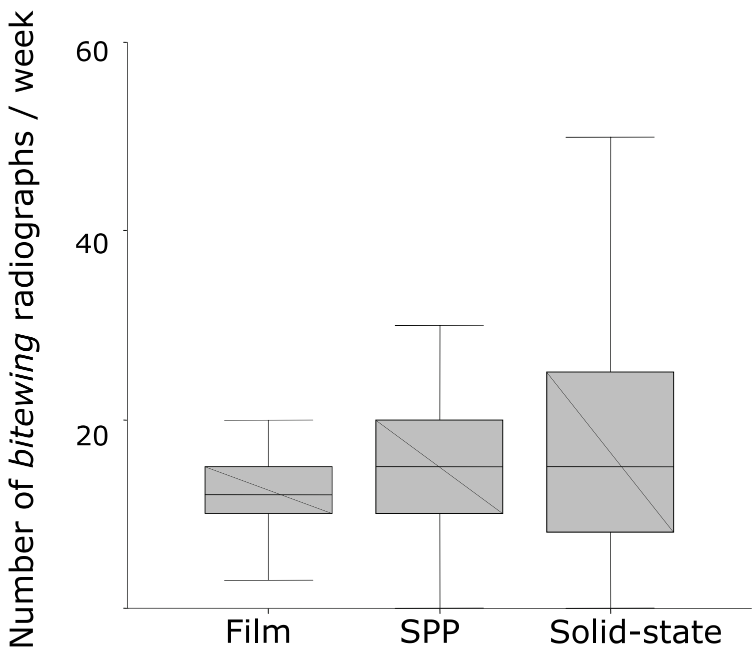


Table 1. Percentages of GDPs reporting taking more, as many or fewer radiographs

	Bitewing		***Periapical***		***Endodontic***	
	SPP	Solid-state	SPP	Solid-state	SPP	Solid-state
More	26	34	33	50	42	64
As Many	74	59	66	46	55	33
Less	0	7	1	4	3	3

SPP = Storage Phosphor plate: n=229; Solid-state: n=112

Table 1 shows the percentages of GDPs taking more, as many or fewer radiographs than before switching to digital radiography. For periapical and endodontic radiographs, significantly more users of solid-state rather than phosphor plate sensors took more radiographs ($P=0.004$ and $P<0.001$, respectively).

For bitewings, more users of solid-state systems rather than phosphor plate systems took more radiographs, although this difference was not significant ($P=0.168$). Nevertheless, 7% of solid-state users reported fewer bitewings than before switching to digital radiography. For all three kinds of radiographs, phosphor plate users state more often than solid-state users that they take as many radiographs as they did before (bitewings, $P=0.009$; periapicals and radiographs during endodontic treatment, $P<0.001$).

Various reasons were mentioned for taking more radiographs than before. The needs for more certainty about the planned or ongoing treatment as well as better diagnosis were the most important reasons for taking more radiographs. Relatively more solid-state users than phosphor plate users mentioned these reasons. These differences were found to be statistically significant ($P=0.009$ for certainty and $P=0.001$ for diagnosis).

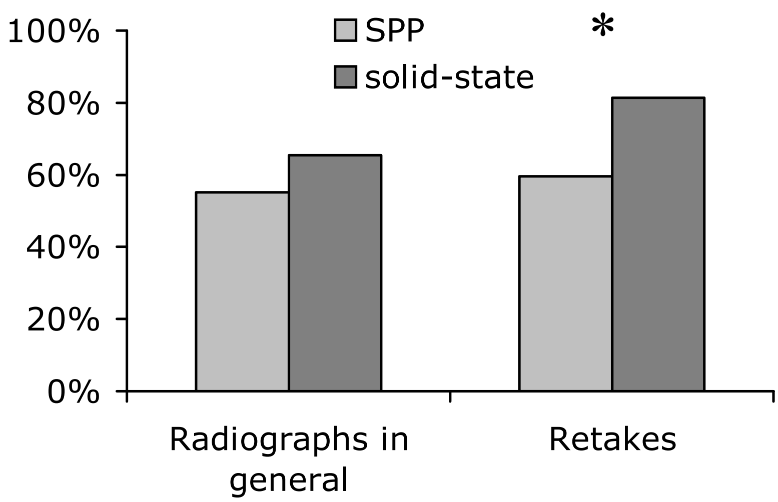
For 17% of GDPs using digital radiography, the idea that digital radiography requires less radiation than conventional film-based radiography was reason enough to take more radiographs. The 'mistakes' were also an important cause for taking more radiographs (10%). Significantly more solid-state users than phosphor plate users mentioned this reason ($P<0.001$). Other reasons mentioned were the quality of the radiographs (2%), extra earnings (3%), making up arrears (3%) and demonstrating the system to the patient. The arrears that were mentioned were caused, according to the GDPs, by a malfunctioning film processing machine (before the conversion to digital radiography). Two GDPs mentioned 'demonstrating the newly bought system to the patient' as a reason for taking radiographs. By taking radiographs of the patient, the GDPs showed how the system works.

As shown in Table 1, a small number (n=22) of GDPs using digital radiography state that they take fewer radiographs than before. Difficulty with the positioning of the detector is the most important reason for taking fewer radiographs (40%). Only users of a solid-state system mentioned difficulties with positioning of the detector. Having difficulties with reading the radiograph on screen resulting in inferior diagnosis is another important reason (32%).

Electronic assessment of root canal length using an 'apex locator' and the process of taking a digital radiograph being more cumbersome both represent almost 10% of the reasons for taking fewer radiographs.

The GDPs using digital radiography were asked whether or not deciding to take or re-take a radiograph was easier after the conversion to digital radiography. Figure 3 shows the percentages of GDPs deciding more easily to take or re-take a radiograph. No significant difference could be found between the two groups of digital systems (P=0.089). With regard to repeat radiographs, significantly more users of solid-state *vs* phosphor plate sensors found it easier to decide to re-take a radiograph than before switching to digital radiography (P<0.001).

Figure 3. Percentage of GDPs reporting taking or re-taking radiographs more readily than before the conversion to digital radiography. *Statistical significance between storage phosphor plate (SPP) and solid-state group



DISCUSSION

Many GDPs using digital radiography take more radiographs than their colleagues using conventional film. Per week, the average number of radiographs taken by film users is 32.5; this rises to 42.8 for phosphor plates and 48.4 for solid-state sensors, representing increases of 32% and 49%, respectively.

There is a possibility that GDPs who use digital radiography have always taken more radiographs than the control group. However, this is unlikely for two reasons. First, we found no differences in terms of gender, age, years in dentistry or other demographic data between GDPs using digital radiography or film.[11] Moreover, a Norwegian study did not report any differences between users of digital *vs* film sensors.[12] Of course, other factors that we did not examine, such as the number of endodontic treatments or implant treatments, could also be a factor. However, the questionnaire was only sent to general dental clinics, and not to endodontic or implant clinics, so one can assume that the confounding effect of those factors for this study is negligible. Moreover, as shown in Table 1, GDPs using digital radiography say themselves that they take more radiographs than they did before the conversion to digital radiography.

The increase of the number of bitewing radiographs was less than the increase of the other radiographs and this may be explained by the existence of better guidelines for bitewing compared with periapical examinations.[13]

Radiation safety is an important issue, with the number of radiographs as well as the dose needed per radiograph determining the radiation dose per patient. Our results show that the number of radiographs taken was greater with digital rather than film radiography. Whilst this means the total radiation dose is higher with digital radiography, the dose needed per exposure is lower. The literature has described in vitro digital dose reductions of 50–94% compared with Ektaspeed film.[1–9,14,15] A questionnaire study by Wenzel and Møystad showed the exposure time using digital radiography was reduced by 55% compared with film.[10]

The dose reduction as a result of shorter exposure times exceeds the increase in dose as a result of the greater number of radiographs taken. However, in the case of solid-state sensors, the dose reduction per exposure has almost been cancelled out by the increase in the number of radiographs taken. What is more, in some cases this may mean the radiation dose is higher than before conversion to digital radiography.

This brings us to the question of why GDPs using digital radiography take more radiographs than GDPs using conventional radiography. Are those extra radiographs taken to obtain more radiological information about the patient, or for other reasons? Of course, the smaller solid-state sensors need more radiographs to obtain at least the same amount of diagnostic information. The results show that 65% of digital users take more radiographs to gain greater certainty about the treatment, or to achieve better diagnosis. Why do digital users need that extra information, whilst film users apparently do not? There is probably a need for more diagnostic information, especially during endodontic treatment and periapical diagnostics (see Table 1). Without any doubt, the relatively short period between exposure and display of the radiograph may tempt GDPs to take more radiographs, as they may view this an improvement of their diagnostic capabilities.

In conclusion, the average patient dose will in most cases be lower when using a digital system compared with previous use of film. For solid-state users who are taking 50% more radiographs with half the dose needed for conventional film, the dose reduction is only 25%. *In vitro* dose reduction studies and digital manufacturers' claims of dose reduction are probably overstated compared with the clinical situation.

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5

The dynamic range of digital radiographic systems

dose reduction or risk of overexposure

ABSTRACT

Objectives:
To investigate the range of diagnostically acceptable digital radiographs and film as a function of exposure time, as well as the relationship to dose reduction and consequences for dental practice.
Methods:
Five systems for intraoral radiography were used to take a series of radiographs, with increasing exposure times, of five different dry bone specimens. Seven observers evaluated the 25 series of radiographs. The observers had to determine which radiographs of each series were acceptable for dental diagnostics and which radiograph of each series they preferred.
Results:
For Ektaspeed Plus film, the exposure time for the preferred radiograph was 0.52 s, with a range of diagnostically acceptable radiographs from 0.23–1.02 s. The preferred radiograph of the solid-state systems required less radiation than film (Sirona, 0.13 s; MPDx 0.35 s). The exposure range of these systems is narrow. In contrast, the exposure range of the phosphor plate systems is very wide. The preferred radiograph of the phosphor plate systems required high exposure (Digora, 1.21 s; Gendex DenOptix, 1.16 s).
Conclusions:
All digital systems require less exposure than film for diagnostically acceptable radiographs, but this is less obvious for preferred radiographs. Solid-state systems alert the dentist when a too long exposure time is used by a lack of image quality; phosphor plate systems, however, produce good quality radiographs even at high exposure times, which may result in an unnecessarily high dose.

INTRODUCTION

The number of General Dental Practitioners (GDPs) using digital radiography is steadily increasing. Two studies on the experiences of GDPs with systems for digital radiography showed that 12–15% of the GDPs in Western European countries currently use digital radiography.[1,2]

Although digital radiography is seen as a modern diagnostic technique, the common principle of radiation safety is unaltered: the desired amount of information must be obtained with the smallest possible amount of radiation. The literature shows that the dose per exposure is generally lower in digital intraoral radiography than in conventional film-based radiography.[3–11] Indeed, manufacturers of digital radiographic systems often present dose reduction as a major reason for GDPs to buy a digital system.

However, the amount of dose reduction has to be questioned, because the dose to the patient is determined not only by the dose per exposure but also by a number of other factors. For example, the size of the active surface of solid-state sensors, which is often smaller than conventional film, requires a higher number of radiographs to be taken to obtain the same amount of diagnostic information.[12] Additionally, positioning digital intraoral detectors is significantly more difficult than positioning film, which may lead to more re-takes.[1] Furthermore, the ease of taking an additional radiograph and the relatively short period between exposure and the display of the radiograph almost certainly tempts GDPs to take more digital radiographs.[12] Taking this into consideration, it is questionable whether the total radiation dose with digital radiography is so much lower than it is with conventional film.

Several studies have investigated the sensitivity of digital sensors.[3,9,10,13–15] However, each of these studies investigated only one of the several aspects of radiological dental diagnostics, e.g. caries, root resorption, and determination of file length and periodontal bone loss. As far as we know, only two studies have investigated several of these aspects at once.[16,17] Nevertheless, a complete study comparing several current digital systems and film on the aspects of exposure latitude and diagnostic value related to dose reduction could not be found.

The aim of this study, therefore, was to investigate the range of diagnostically acceptable digital radiographs and film as a function of exposure time and to relate this to dose reduction.

MATERIALS AND METHODS

Intraoral radiographic systems

Radiographs were taken of five different dry bone specimens of different jaw regions including incisors, canines, premolars and molars. Five systems for intraoral radiography (two solid-state systems, two phosphor plate systems and film) were used to produce the radiographic images. The systems are listed in Table 1.

The Digora scanner must be calibrated at installation in order to relate the output of the X-ray unit to the scanner response. For the calibration, an imaging plate has to be exposed with the maximum exposure that will be used with patients, which in our situation was 0.25s. According to the user's manual this will eliminate all future overexposures. The brightness offset also can be adjusted during the calibration procedure, resulting in better visibility of hard tissues or of soft tissues. However, we did not enter a brightness offset, so no extra pre-processing was applied to the scanned radiographs. The Gendex DenOptix scanner does not have a calibration procedure, so the default settings of this scanner were used. Neither of the solid-state sensors has a calibration step.

Table 1. Manufacturers and specifications of the digital systems and film used in this study.

Detector	*Manufacturer*	*Active surface*	*Pixel size*
Sidexis full-size	Sirona Dental Systems GmbH, Bensheim, Germany	34 x 26 mm	39 μm
MPDX no. 2	Dental Medical Diagnostic Systems Inc. Westlake Village, California, USA	33 x 27 mm	46 μm
Digora FMX	Soredex, Helsinki, Finland	40 x 30 mm	64 μm
DenOptix	Dentsply International Gendex division, York, Pennsylvania, USA	40 x 30 mm	82 μm
Ektaspeed Plus	Eastman Kodak, Rochester, New York, USA	41 x 31 mm	

To protect phosphor plates against exposure by daylight, the plates were put in plastic envelopes and scanned immediately after exposure. The DenOptix phosphor plates were mounted on the read-out carousel in a room with dimmed background light. The original software accompanying the different systems was used for image capture. No image processing was done to enhance image quality other than the standard pre-processing provided by the system under investigation. All images were saved as 8-bit bitmaps (BMP).

Conventional films were developed using an automatic X-ray film developer (Dürr Dental XR 24; Dürr Dental, Bietingsheim-Bissingen, Germany) at a temperature of 27°C, using fresh Readymatic dental developer and Readymatic dental fixer (Eastman Kodak, Rochester, NY).

X-ray source and exposure data

Exposures were made with a Heliodent MD multi-pulse X-ray unit (Siemens, Bensheim, Germany) operating at 60 kV and 7 mA, with a filtration of 1.5 mm Al equivalent and a half-value layer (HVL) of 1.9 mm Al. The X-ray beam was collimated to a 3.3 cm x 4.3 cm rectangle at the end of the spacer cone. The focus–detector distance was 30 cm. A 30 mm thick object, consisting of 8 mm Lucite and 22 mm water, was placed between the X-ray source and the dry jaw specimens as a soft tissue-equivalent material. Radiographs were taken of the dry bone specimens using the full timer range of the Heliodent MD (0.01–3.20s).

All five dry bone specimens were radiographed with the five radiographic systems, resulting in 25 series. A series contained all the radiographs of one bone specimen taken with one radiographic system at successive exposure times. Images that were extremely overexposed or underexposed were excluded from the series. Therefore, some series did not contain the full range of exposure settings that is possible with the timer of the Heliodent MD. The total number of radiographic images included in this study was 530.

Observer sessions

Eight observers (four dentists and four dental radiologists) evaluated the radiographs in two different sessions with an interval of at least 1 day. Each session contained 25 series of images. The series were shown to the observers in random order.

A computer program, ACDsee® version 3.0 (ACD Systems, Victoria, British Columbia, Canada), was used to show the digital radiographs. An example of a series of radiographs in the ACDsee® program is shown in Figure 1. The computer monitor was an NEC MultiSync FP1370 21" with a resolution of 1280 x 1024 pixels (NEC, Tokyo, Japan). The monitor was adjusted using the SMPTE (Society of Motion Picture and Television Engineers) test pattern.[18,19] Conventional films were mounted in Rinn Eezeemount non-transparent mounting frames (Rinn Corporation, Elgin, IL) and were evaluated on a lightbox. Observer sessions took place in a room with dimmed background light. To avoid adverse effects of zooming, all digital radiographs were shown in their original dimensions.[20,21] The observers were not allowed to make any adjustments to the images that could improve or decrease image quality.

Figure 1. Example of a series of radiographs in the ACDsee® program.
In the observer sessions the radiographs were shown in their original dimensions

The radiographs were presented to the observers per series. Using a 'mouse wheel', observers could easily scroll backward and forward through the series. The observers had to determine (a) which radiographs of each series were acceptable for dental diagnosis and (b) which radiograph of each series they preferred. The following instructions were given to the observers: (a) select the radiographs at both ends of the exposure range that produced diagnostically useful images (minimum and maximum dose) and (b) select the radiograph you prefer for dental diagnosis. The observers were asked to look at the images bearing in mind the normal diagnostic tasks they usually perform, e.g. caries diagnostics, detection of periapical radiolucencies, assessment of the periodontal bone level and the periodontal ligament space. They were instructed to select radiographs that would be useful for such tasks. Owing to misinterpretation of these instructions, the data of one observer could not be used and were therefore excluded from this study. Thus, the final outcomes are based on the data of seven observers. For each series the average 'minimum', 'preferred' and 'maximum' exposure time was calculated.

For statistical analysis, descriptive statistics, analysis of variance and post-hoc tests (Bonferroni) were performed using SPSS 9.0 (SPSS Inc., Chicago, IL). Differences were considered statistically significant at $P<0.05$.

RESULTS

Preferred radiographs

The average exposure times for preferred radiographs for each image receptor are shown in Figure 2 (next page). The exposure times for preferred radiographs taken with the two phosphor plate systems are rather long and have a large standard error. The preferred exposure time for Ektaspeed Plus film is also rather long, but with a small standard error. The MPDx solid-state sensor requires an almost three times longer exposure time than the Sirona sensor (0.35 s *vs* 0.13 s). Both phosphor plate systems significantly differed from the solid-state systems and film ($P=0.016–0.001$).

Figure 2. Mean exposure times (with standard error) of four digital radiographic systems and Ektaspeed Plus film for radiographs that observers 'prefer' for common dental diagnostic tasks

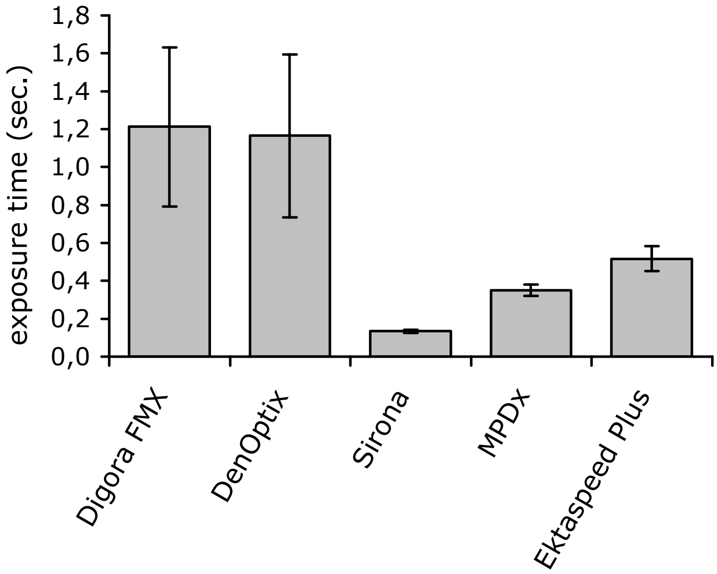
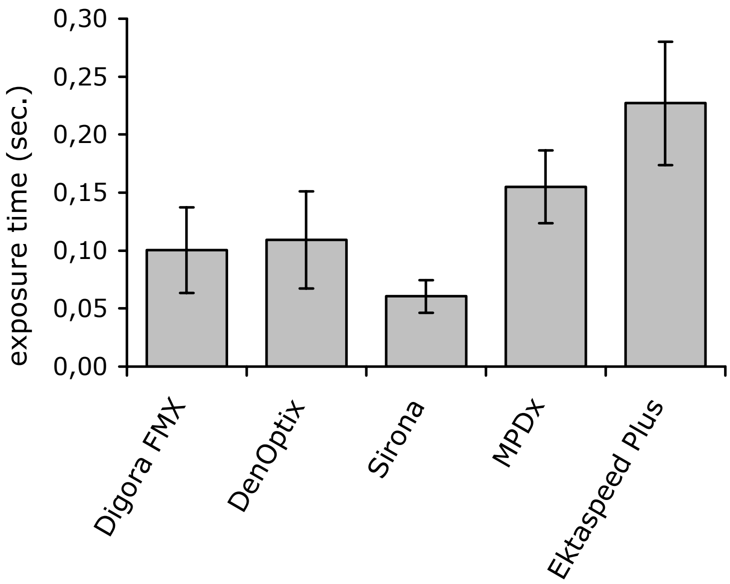


Figure 3. Minimum exposure time required for radiographs of "just acceptable" diagnostic quality



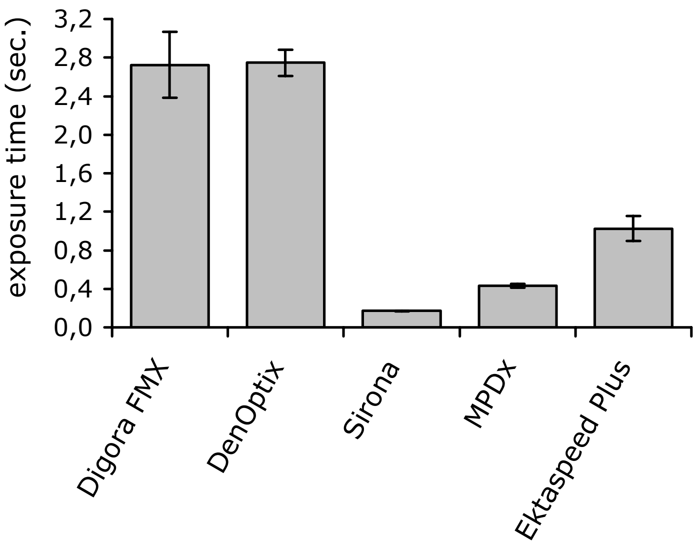
Minimum exposure time

Radiographic information must be obtained with the smallest possible amount of radiation. The minimum exposure times needed for radiographs that have an adequate diagnostic quality according to our observers are presented in Figure 3. All digital image receptors need only a very short exposure time to produce a diagnostically just acceptable radiograph. All digital systems, except the MPDx system (P=0.104), differed significantly from Ektaspeed Plus film (P<0.001). No statistically significant difference was found between the digital radiographic systems, except for the difference between the Sirona sensor and the MPDx sensor (P=0.008).

Maximum exposure times

Overexposure causes either a too dark radiograph or, in the case of solid-state systems, artefacts such as blooming. The maximum exposure times for radiographs that were useful for dental diagnostics are presented in Figure 4. Both phosphor plate systems still produce acceptable radiographs at very high radiation doses, in contrast to both solid-state systems that already show blooming at relatively low doses. The maximum exposure times of the phosphor plate systems differ significantly from the solid-state systems and film (P<0.001). Moreover, Ektaspeed Plus film has a significantly higher maximum exposure time than both solid-state sensors (P<0.001). No statistically significant difference was found between both solid-state sensors.

Figure 4. Maximum exposure time resulting in radiographs of "just acceptable" diagnostic quality



DISCUSSION

Subjective image quality, as measured in this study, can be used to compare different systems, especially when the observers are aware of the common range of diagnostic tasks they are performing in general dental practice. The outcomes would have been more specific if one particular diagnostic problem had been studied at a time, but we preferred an approach that is more comparable with the common situation in dental practice, and thus with the way GDPs normally use radiographic images.

The ALARA (as low as reasonably achievable) principle holds that the desired amount of information must be obtained with the smallest possible amount of radiation. At a lower dose, noise will increase and the diagnostic value of the radiograph will decrease. Therefore, it is important not to lower the dose below this threshold value. Reducing exposure time to the lowest possible level without compromising diagnostic value does not involve any expense and is therefore obligatory according to the ALARA principle.

Based on the minimum acceptable dose, all digital systems gave a reduction compared with E-speed film: Sirona reaches approximately 70% reduction followed by both phosphor plate systems (50% reduction) and MPDx (30% reduction). A study of the use of digital radiography in general dental practice showed that GDPs using digital systems reported a dose reduction of 55% on average compared with film.[22] This is a dose reduction similar to that found in the current study for the Sirona sensor. It is, however, somewhat higher than our results for the MPDx sensor, which would produce an image that is below the acceptable threshold. Therefore, in the case of solid-state sensors, careful selection of the most appropriate exposure time by the dentist is required.

Although the observers in this study believe that the 'minimally acceptable' radiographs are useful for dental diagnostics, the noise increases compared with the preferred radiographs, which has a negative effect on the visibility of structures on the radiographs. It is therefore presumed that GDPs select higher exposure times that give 'nicer' (less noisy) radiographs. The doses will rise to the 'preferred image quality' values. This is very unfavorable, especially for the phosphor plate systems. According to this study, the preferred image quality of phosphor plate systems requires ten times more radiation than the minimally acceptable dose. Moreover, phosphor plate systems require more radiation than E-speed film to produce images of preferred quality. So it is important to note that for phosphor plate systems the exposure range extends to rather high values. This is another reason to emphasize the need for careful selection of exposure times.

This study makes a distinction between minimally acceptable radiographs and preferred radiographs. According to the observers, both kinds of radiographs are useful for dental diagnostic tasks. We did not compare the possible effects of minimally acceptable radiographs and preferred radiographs on the diagnostic outcome. There could be, at least, an influence on the speed or easiness of diagnosis. Whether there is an influence on the correctness remains to be seen. It is therefore possible that, for solid-state systems that produce preferred radiographs at very low doses (such as the Sirona sensor), it is justifiable to use doses that give preferred radiographs instead of doses that give minimally acceptable radiographs. This illustrates the fact that digital radiography does not automatically imply a dose reduction compared with film-based radiography. In fact, in comparison with E-speed film, a reduction in radiation dose for preferred radiographs is seen only for solid-state systems.

To get a clear view of the complete dynamic range of digital systems and film, we also looked at the maximum exposure times that produced images of an acceptable quality. For phosphor plate systems, maximum exposure times are close to or at the end of the timer range of the X-ray source. The radiographs from phosphor plate systems remain good even at very long exposure times. On the one hand this means no re-takes are needed when overexposing phosphor plates. On the other hand, a phosphor plate system user can accidentally give a higher dose than strictly required without being alerted by a lack of image quality.

For solid-state systems, preferred and maximum exposure times do not differ much. This may easily result in overexposed images, which then require re-takes. Therefore, it is always advisable to use an exposure table.

In conclusion, the range of diagnostically acceptable digital radiographs differs according to the make of the system. It is true that all digital systems require less radiation than film for diagnostically ‘just acceptable’ radiographs, although the amount of reduction differs significantly. For diagnostically ‘preferred’ radiographs, dose reduction is less obvious. The large difference in dose reduction and the rather small dynamic range of solid-state sensors requires careful selection of the most appropriate exposure time. Phosphor plate systems do not indicate when using a too long exposure time. For these reasons an exposure table, calibrated to the digital system and to the X-ray source, is essential.

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6

The effect of the dynamic range of digital systems on diagnostic accuracy in caries diagnosis

ABSTRACT

Objectives:
To investigate the relation between subjective image quality within the dynamic range of digital systems and the diagnostic accuracy of caries diagnosis.
Methods:
Four digital systems (Digora Optime, Dürr VistaScan, Gendex Visualix HDI and Instrumentarium Sigma) were used to take series of radiographs with increasing exposure times under conditions comparable to a clinical radiographic examination. Nine bitewing simulations containing a total of 90 extracted unrestored premolars were radiographed. Four radiologists and four general practitioners were asked to determine which radiograph of each series they preferred and which radiograph of each series was just acceptable for caries diagnosis. Next, in three random sessions ('preferred', 'just acceptable' and 'unacceptable') the observers were asked to assess caries depth on a four point scale. The observers' scores were compared with the results from a histological examination after sectioning the teeth. A total of 65 surfaces were incorporated in the study. Data were analysed using the statistical theory for multivariate discrete data.
Results:
The preferred and just acceptable exposure times gave a comparable diagnostic accuracy and both outperformed the unacceptable radiographs. However the effect differed for the two observer groups and caries depth; radiologists outperformed general practitioners in preciseness and general practitioners had higher diagnostic accuracy on sound surfaces and dentin caries.
The exposure time to produce a radiographic image of preferred quality with both phosphor plate systems was high; the just acceptable image quality of these systems required also a rather long exposure time of 0.25 seconds.

Conclusion:

Diagnostic accuracy for caries diagnosis is comparable for preferred as well as just acceptable radiographic images; in order to keep the dose as low as possible the shortest exposure time producing images of an acceptable diagnostic quality should be used.

INTRODUCTION

In caries diagnosis radiography plays an important role. In general the use of radiographs increases the number of caries lesions that are detected.[1] Currently, the performance of digital radiographs for caries diagnosis resembles that of analogue film based radiography.[2-5] In spite of this, many studies have demonstrated the tendency of radiographic diagnosis to underestimate the severity of lesions.[6-8]

Radiation dose influences the detection of caries lesions.[9] For CCD (Charge Coupled Device)-based X-ray detectors the dynamic range in which acceptable radiographs are produced is rather narrow. Phosphor plate systems on the other hand have a very wide dynamic range.[10] The ICRP (International Commission on Radiological Protection) expressed recently concern about the influence of the dynamic range of digital systems on patient dose. In 2004 'Publication 93' entitled 'Managing patient dose in digital radiology' was presented by the ICRP.[11] The commission literally states: 'Although digital systems have the potential to reduce patient doses, they also have the potential to significantly increase them'. This statement directly follows from the observation that with digital (phosphor plate) systems an overexposure can occur without an adverse impact on image quality.
Overexposure may not be recognized by the radiologist or radiographer. The overexposed radiographic image even may look "nicer" and therefore the diagnostic value seems to be higher.

Rapid developments occur in digital radiography, which are intended to increase the image quality, but often have implications for the patient dose. For example, new digital systems were introduced that have higher spatial and greyscale resolutions but also require higher radiation dose then the first digital systems. Therefore, determining which exposure level is the 'lowest possible' for digital systems is an important task that follows directly from the ALARA principle and has a strong link to ICRP publication 93.

An *in vitro* study with histological validation is a very robust way to test radiographic systems, for example to determine the lowest possible exposure level for various diagnostic tasks; however it is a very time and material consuming method. It would be a lot easier if the (subjective) expert assessment of the image quality of radiographs of a dry bone specimen or other test object was a reliable indicator for the diagnostic value of that system and/or dose setting. Of course, such an expert assessment should have a strong relation with *in vivo* or at least *in vitro* histological validation, as histological validation at this moment is considered to be the preferred reference method.[12,13]

In view of the above, the aim of our study is to determine if a better subjective image quality corresponds with a higher diagnostic accuracy for caries detection and how this relates to the applied exposure time.

The null hypothesis to be tested was that no significant differences exist between three subjectively chosen dose settings corresponding with images of different diagnostic quality on diagnostic accuracy for caries diagnosis. The model used to compare the various dose settings and systems was the diagnostic performance of the digital systems with respect to the diagnosis of proximal caries.

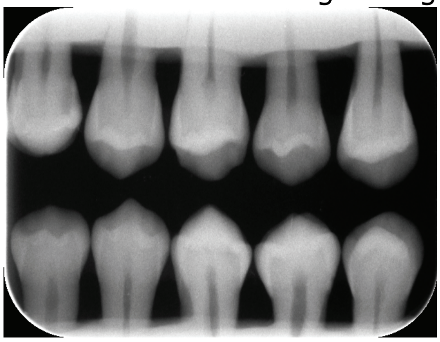
MATERIALS & METHODS

Image acquisition

Ninety extracted human premolars were selected. Based on visual and radiographic examination the proximal surfaces of these premolars ranged from sound to dentinal lesions. The teeth were mounted in groups of five in plaster blocks. Two blocks at a time were placed in a jig to simulate a bitewing radiograph (Figure 1, next page). Nine different bitewing-sets were radiographed, with a total of 72 different premolars to be examined. Only the left tooth surface of each proximal area was assessed, as observations of disease from two surfaces in the same tooth may be statistically dependent on each other.[14]

Figure 1. Two blocks with premolars (A) to simulate a bitewing radiograph (B)


A


B

Between the tube end of the X-ray source and the tooth blocks a 30 mm thick soft tissue equivalent material was placed, consisting of 8 mm Lucite and 22 mm water. Series of radiographs were taken of the bitewing-sets using the full range of the exposure timer (0.01 - 3.20 seconds) of the Siemens Heliodent MD X-ray unit (Siemens, Bensheim, Germany) operating at 60kV, 7mA with a filtration of 1.5 mm Al equivalent. The focus-detector distance was 30 centimeters. The full timer range was used because the researchers beforehand did not know which radiograph the observers would prefer, that could even be up to 3 seconds.

Using this set up images were produced with 4 different digital systems. Two charge coupled device (CCD) systems; the Instrumentarium Sigma (Instrumentarium, GE Healthcare Finland Oy, Tuusula, Finland) and the Gendex Visualix HDI (Gendex Dental Systems, Des Plaines, Illinois, USA); and two storage phosphor plate systems; the Digora Optime (Soredex, GE Healthcare Finland Oy, Tuusula, Finland) and the Dürr VistaScan (Dürr Dental GMbH&CO. KG, Bietigheim-Bissingen, Germany). The original manufacturers' software of all four systems was used to acquire the radiographs and no image processing was applied else than the standard pre-processing of the systems themselves.

The Instrumentarium Sigma sensor can be connected to the Instrumentarium Focus X-ray tube (same characteristics and settings as the Siemens tube) which gives the option to automatically control the exposure of the tube by the software of the sensor. This function is called 'automatic exposure control' (AEC) and switches of the tube when the sensor is 'optimally' exposed. Apart from the series taken with the Siemens Heliodent tube and the Sigma sensor, we also took an X-ray of every bitewing-simulation using the Instrumentarium Focus tube linked to the Sigma sensor with the AEC option switched on. We added this radiograph to the respective series.

Subjective image quality

The series of radiographs acquired with each of the digital sensor systems were presented to eight observers. The radiographs were displayed on a 20-inch Philips Brilliance 200P TFT monitor (Philips, Eindhoven, The Netherlands) at a resolution setting of 1600x1200 pixels. Contrast and brightness of the monitor were calibrated using the SMPTE test pattern.[15] The observation sessions took place in a room with dimmed background lighting. The observers were not allowed to change brightness and contrast settings of the monitor.

The AEC-image of the Sigma sensor was included in each Instrumentarium Sigma-series. The series of each system were given in random order. Using a 'mouse-wheel' the observers could easily scroll backward and forward through the series. The observers were asked to determine for each series (a) which radiograph they preferred for optimal caries diagnosis, and (b) which radiograph was just acceptable for caries diagnosis. The average preferred and just acceptable exposure time for each system were calculated from the choices of the observers. The not acceptable exposure time was chosen one standard deviation below the mean of the just acceptable exposure time. For CCD as well as phosphor plate systems this resulted in an exposure time that was two steps lower on the timer scale of the Siemens Heliodent. The images selected as described in the previous paragraph for each sensor system were used to determine the diagnostic accuracy.

Diagnostic accuracy

Series containing preferred, just acceptable or unacceptable radiographs which were selected using the subjective image quality procedure described in the previous section were randomly presented to eight observers. Four of them were employed at the radiology department with much experience in caries diagnosis on digital radiographs; the other four observers were general practitioners having some experience with digital radiographs. The viewing conditions were identical to the conditions described in the *'subjective image quality'* paragraph

The observers were asked to score caries depth on a 4 point scale:

0 = sound proximal surface;
1 = radiolucency in first half of enamel;
2 = radiolucency up to the amelodentinal junction (ADJ)
3 = radiolucency into dentine.

Before the start of the sessions the observers were told that the distribution of the lesion-depths was about 25%. The observers made 6912 assessments of 108 radiographs in total (4 systems x 3 categories of image quality (exposure settings) x 9 simulated bitewing images x 8 surfaces per image).

Histological validation

True caries depth was determined using histological examination. The teeth were sectioned using a Leica SP1600 saw microtome (Leica Microsystems, Nussloch, Germany) into 300 µm slices and examined with a Zeiss Stemi SV 6 stereomicroscope (Carl Zeiss, Oberkochen, Germany) by two experienced investigators. The same 4 point scale was used as presented above. The two investigators independently assessed the teeth. In case of disagreement they made a joint decision.

A total of 7 surfaces were excluded from the study because the teeth were damaged or had root or occlusal caries. The final material consisted of 65 proximal surfaces from 65 teeth.

Data analysis

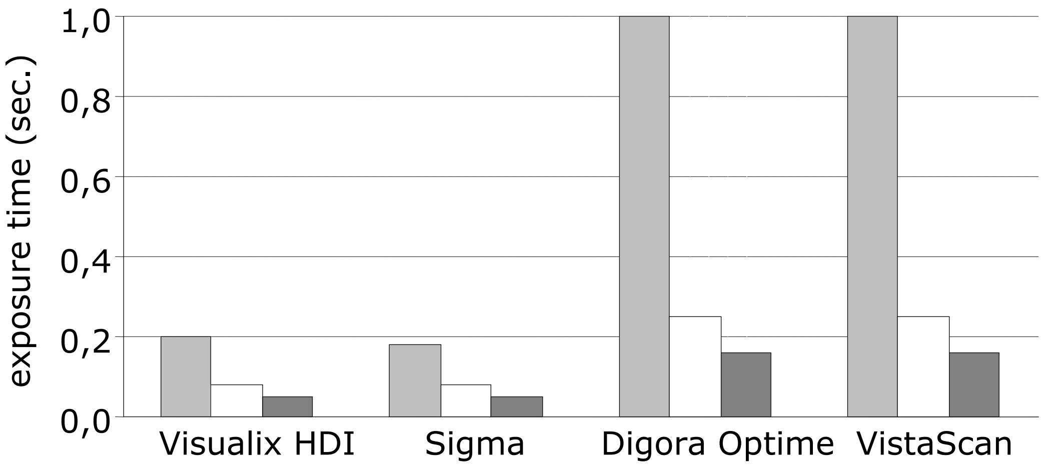
The judgments of the eight observers are represented in a four-fold frequency table: exposure setting * system * gold standard * judgment, where judgment represents the dependent variable that measures the probability of detecting the four caries depths. This type of data can be analysed using the statistical theory for multivariate discrete data.[16] In our case the relation between the gold standard and the observers' judgments is crucial. When this relation is ideal the diagnosis is perfect: i.e. sensitivity and specificity are 1.00. When, for example, for two different exposure settings the relation to the gold standard is the same, both settings have the same diagnostic accuracy, because sensitivity and specificity depend on the relation between gold standard and observers' judgment. For all tests a significance level of $\alpha = 0.05$ is used. Differences were considered statistically significant when $p \leq 0.05$.

RESULTS

Subjective image quality

The exposure times representing the preferred, just acceptable and unacceptable subjective image quality are presented in Figure 2.

Figure 2. Subjective image quality: exposure times for preferred, just acceptable and unacceptable image quality.



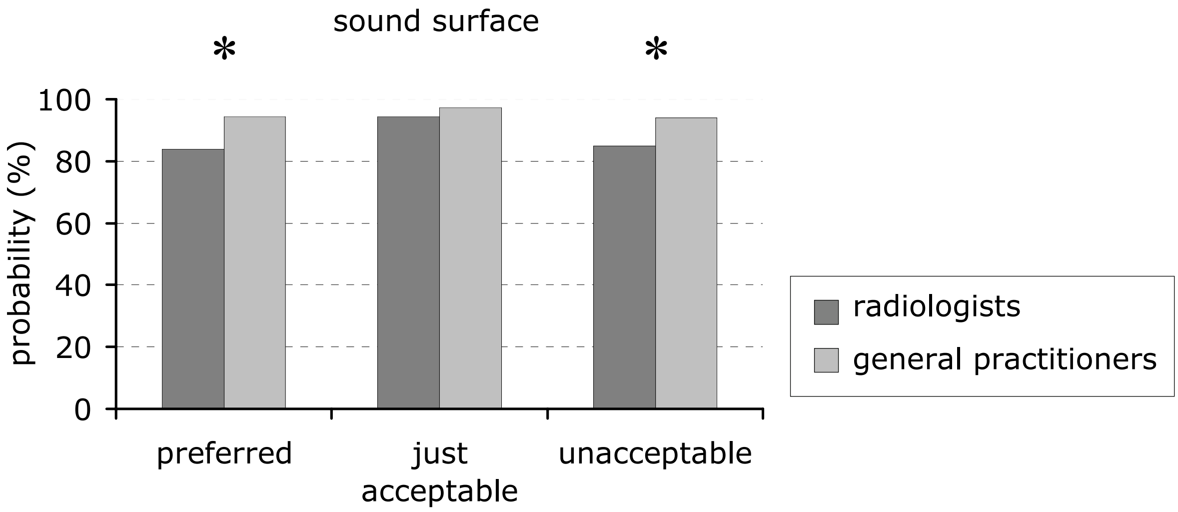
	Visualix HDI	Sigma	Digora Optime	VistaScan
preferred	0,20	0,18	1,00	1,00
just acceptable	0,08	0,08	0,25	0,25
unacceptable	0,05	0,05	0,16	0,16

The preferred image from the series taken with the Instrumentarium Sigma sensor appeared to be the image that was taken with the automatic exposure control function (AEC) switched on. The preferred image of the Visualix HDI sensor took more or less the same exposure without automatic exposure control. The exposure time to produce a radiographic image of preferred quality with both phosphor plate systems was high (1 second!), and even the just acceptable image quality of those systems required a rather long exposure time of 0.25 seconds. The exposure time resulting in an image of unacceptable quality was chosen such that it was below the just acceptable exposure time but not interfering with the standard deviation of the just acceptable exposure time.

Objective diagnostic performance

The statistical comparison between the *preferred, just acceptable and unacceptable* dose settings showed a statistically significant difference in diagnostic accuracy for caries diagnosis between these settings ($\chi^2 = 122.53, df = 45, p < 0.0001$). Overall, the just acceptable exposure times gave a higher diagnostic accuracy than the preferred and unacceptable exposure times. With respect to the diagnostic accuracy for caries diagnosis, radiologists showed a significantly different probability for correct caries detection then the general practitioners do ($\chi^2 = 51.17, df = 9, p < 0.0001$). However, these overall findings should be put in the perspective of the interaction between the exposure setting and the expertise of the observers ($\chi^2 = 29.63, df = 14, p = 0.0086$). This difference appears in three caries-depth categories, namely sound surfaces, enamel caries and dentin caries. Figure 3 shows the probability of correct sound surface detection for the two observer groups under the three exposure conditions.

Figure 3 Probability of correct sound surface diagnosis (*= statistically significant).



For general dental practitioners the exposure condition does not influence the probability of correct sound surface diagnosis. The radiologists showed a higher probability on just acceptable radiographs. Compared to the general practitioners the radiologists have a significantly lower probability for correct sound surface diagnosis on preferred and unacceptable radiographs.

Figure 4 Probability of correct enamel caries diagnosis (* = statistically significant).

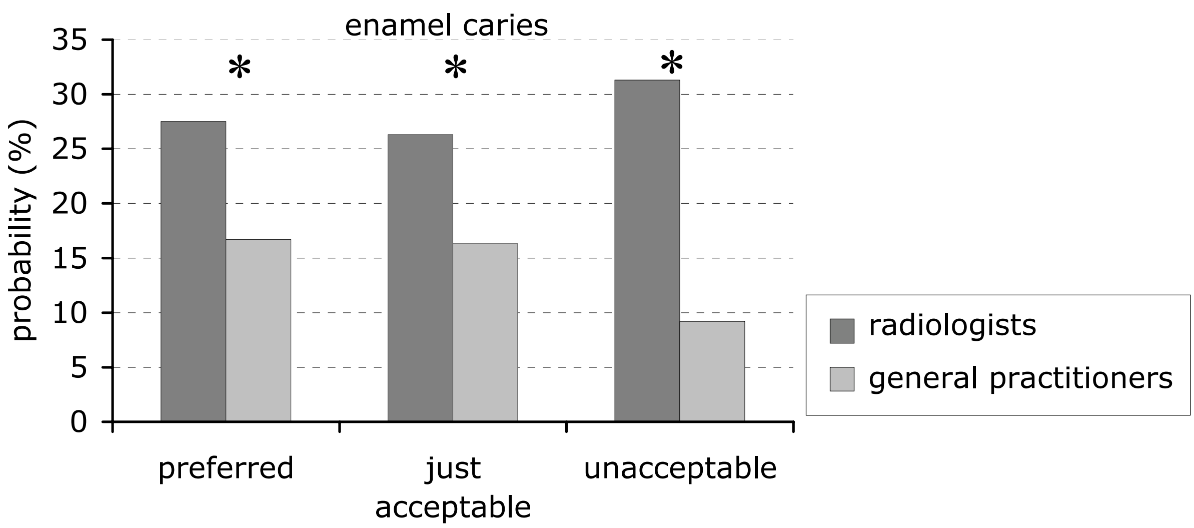


Figure 4 shows the probability of correct enamel caries diagnosis. Overall radiologists have a 10 to 20 percent higher probability for correct enamel caries diagnosis. This results in a significantly better performance on enamel caries detection for all exposure conditions than the general practitioners.

Figure 5 Probability of correct dentin caries diagnosis (* = statistically significant).

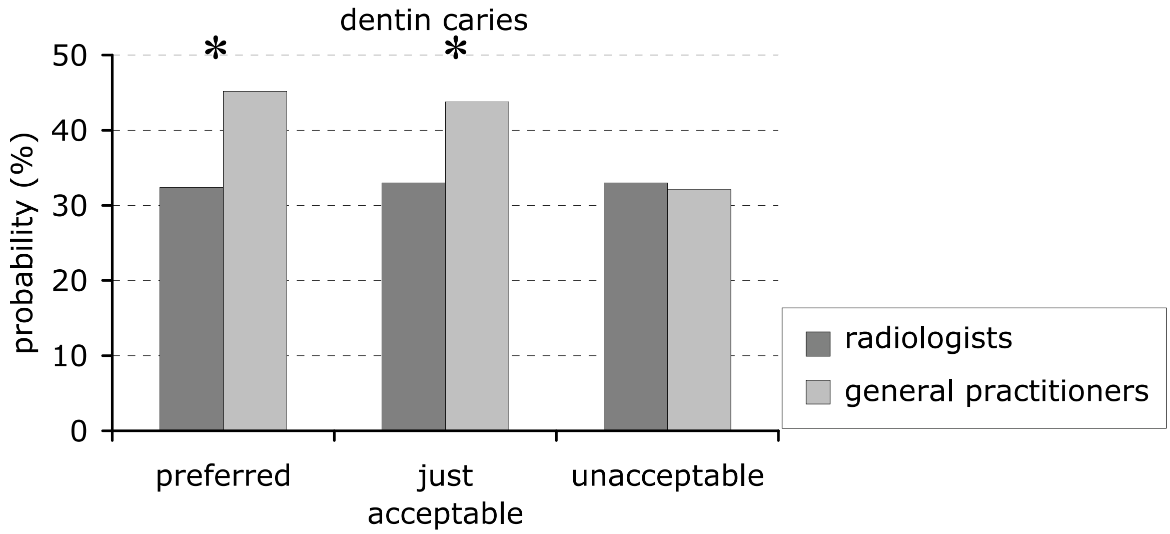


Figure 5 shows the probability of correct dentin caries diagnosis. For radiologist the exposure condition does not have an effect on the probability of correct dentin caries diagnosis. General practitioners have a significantly higher probability of correct dentin caries diagnosis on subjectively preferred as well as just acceptable radiographs.
The probability for correct detection of caries up to the amelodentinal junction has not been displayed because the low percentages of this category, and because differences between exposure conditions as well as observer groups were absent.

DISCUSSION AND CONCLUSIONS

Both observer groups differ in the way the exposure condition influences the caries diagnosis. For radiologists the exposure condition influences diagnostic accuracy for the diagnosis of sound surfaces, for general practitioners the task 'dentin caries detection' is affected by the exposure condition. In general it could be concluded that general practitioners tend to go for 'the extremes'; no caries or dentin caries, maybe caused by the underlying decision of 'drill or do nothing'? Radiologists seem to diagnose the radiographs more precisely, which causes a lower probability for dentin caries in favor of a higher probability for enamel caries detection. Translated to the 'drill or do nothing' query for the radiologists this results in a more expectant approach, assuming that enamel caries will not be treated, except for prophylactic treatment.

The difference in diagnostic accuracy between subjectively preferred and just acceptable radiographs for sound surface detection may be caused by the slightly overexposed appearance of the preferred radiographs. For meticulously diagnosing observers this might give the idea that in the outer part of the enamel small carious lesion are present. Those observers will choose 'enamel caries' instead of the correct 'sound surface' causing a lower probability for preferred radiographs then the less meticulously diagnosing observers.

The difference in exposure between preferred and just acceptable radiographs with respect to caries diagnosis (enamel caries, ADJ-caries and dentin caries) does not cause a difference in diagnostic accuracy. For sound surface detection the just acceptable radiographs even give a better diagnostic accuracy, especially for radiologists.

Although no differences were found in diagnostic accuracy between the phosphor plate systems and the CCD-systems in the three exposure categories, the absolute dose differs to a great extent. The results of the subjective image quality part of this study underline the concern of the ICRP committee that is expressed in Publication 93.[11] When the preferred image quality is selected using phosphor plate systems, indeed the patient dose increases significantly. It is important to realize that an increased exposure of phosphor plate systems does not give immediate feedback by a reduced image quality. This makes it more difficult to recognize overexposure. On the other hand, CCD-systems show overexposure by the so called "blooming" effect of the radiograph. Therefore, a quality assurance program is especially important for phosphor plate systems to prevent unnecessary high doses. Although the absolute doses are lower for CCD-systems, a quality assurance program could give up to 60% dose reduction for these kind of sensor systems as well.

It seems that both phosphor plate systems tested in this study require a higher radiation dose for the just acceptable image quality than the somewhat older systems (Digora FMX and Denoptix) that were tested in a study by Berkhout *et al.* in 2004.[10]

Almost ten years ago Huysmans *et al.* already demonstrated that exposure time for the first Digora system could be reduced considerably compared to E-speed film without adverse effects on caries diagnosis.[17] Although, as mentioned in the introduction, digital systems are rapidly 'improved' this does not mean exposure levels nowadays are lower compared to ten years ago. Taking into account the longer focus to image plate distance used in the study by Huysmans *et al*. and the higher mAs-value, the exposure time they found as not reducing the diagnostic performance for the old Digora systems is about 20% shorter than the just acceptable level in our study with the new Digora Optime.

The overall results in our study indicate that the preferred radiographs do not give a better diagnostic accuracy than the just acceptable radiographs. It follows directly from the ALARA-principle that for caries diagnosis an exposure level not higher than the subjectively 'just acceptable' should be applied, because of the fact that applying higher doses does not benefit diagnostic accuracy of caries diagnosis.
The ICRP publication 93 suggests to review diagnostic reference levels when introducing new digital systems. Based on this study we recommend to determine the subjectively 'just acceptable' radiation dose when implementing a new digital system, as a starting-point to meet the recommendation of the ICRP.

In conclusion, diagnostic accuracy for caries diagnosis is comparable for preferred as well as just acceptable radiographic images, so a higher radiation dose than the subjectively determined just acceptable dose should be avoided.

It is recommended to determine the 'just acceptable' dose level as a contribution to a procedure of quality control as suggested by the ICRP.

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7

Detection of proximal caries with high resolution and standard resolution digital radiographic systems

ABSTRACT

Objectives:
The aim of this study is (1) to compare the diagnostic accuracy of the high resolution setting and the standard resolution setting of four digital imaging systems for caries diagnosis, and (2) to compare the effect on the diagnostic accuracy of reducing in size the high resolution images to the standard resolution dimensions and vice versa.

Methods:
Ninety extracted human premolars were mounted in groups of five in plaster blocks, containing four test teeth and one non-test tooth. Two blocks at a time were placed in a jig to simulate a bitewing radiograph. X-rays were taken using four digital systems, each at two resolution settings (Planmeca Dixi2, Gendex Visualix HDI, Dürr Vistascan, Digora Optime). Next the teeth were sectioned and a total of 65 surfaces were incorporated in the study. Additionally the bi-cubic interpolation method was applied to reduce the high resolution original images and to enlarge the standard resolution images. The original, reduced and enlarged images were randomly shown to five observers in two random sessions. The observers were asked to assess caries depth on a four point scale. The observers' scores were compared with the results from a histological examination. Data were analysed using the statistical theory for multivariate discrete data. Cohen's kappa was used to determine the agreement with the gold standard.

Results:
Non of the comparisons between the spatial resolution settings as well as the comparisons between increased or reduced image size and the original image sizes showed significant differences in the probability of caries detection (χ^2 = 26.59, df = 26, p ~ 0.50).

The four digital systems used in this study differ significantly in the probability of caries detection (χ^2 = 41.55, df = 24, p < 0.02). Compared to the gold standard the Gendex Visualix HDI CCD-sensor has the highest measure of agreement (κ = 0.31).

Conclusion:

Caries diagnosis does not improve when using high resolution settings compared to the standard settings. The use of bi-cubic convolution interpolation for zooming has no detectable effect on caries diagnosis and therefore is recommended to use when enlarging or reducing radiographs. The probability of caries detection, however, was different for the sensor systems of the different manufacturers.

INTRODUCTION

Radiography is, besides clinical examination, the most important tool for diagnosing proximal carious lesions in dental practice. Currently the performance of digital radiographs for caries diagnosis resembles that of analogue film based radiography.[1-5] Different approaches have been applied to improve the digital systems, such as software filters to make relevant information in the raw image more evident[6], enlargement of *greyscale* resolution , and recently, increased *spatial* resolution. The increase of the spatial resolution of CCD-sensors (Charge Coupled Device) is done by reducing the size and pitch of the pixels. As a result, the total number of pixels in the sensor increases, when the active area of the sensor is kept the same.

Theoretically, *spatial* resolution can be expressed as the pixel size or as dots per inch (dpi). It must be emphasized, however, that this is not the only parameter that determines the effective resolution of the imaging device. Greyscale resolution as well as the noise in the image does also affect the final appearance of the image. Therefore the number of 'line pairs per millimetre (lp/mm)' that are visible in an image is also used to define the spatial resolution. The influence of the spatial resolution on the diagnostic outcome has recently been studied with respect to the detection of root fractures, by comparing a high-resolution CCD-sensor (15-20 lp/mm) and a phosphor plate system (8 lp/mm).[7] The authors speculate that the differences in sensitivity in detecting root fractures are caused by the differences in spatial resolution of the different systems.

We have found only one study that compared in particular the influence of spatial resolution on the diagnostic outcome for caries diagnosis. For that study a comparison was made between radiographs scanned at different resolutions.[8] The confidence of the diagnosis increased with increased scanning resolution, but no difference was found for caries detection between scanning resolutions 300 dpi. and 600 dpi. Other studies have compared the influence of displayed image size on proximal caries detection. These studies, however, made use of only one (scanning) resolution and only magnification or size reduction of the displayed image was used.[9,10]

Several solid-state sensors (CCD and CMOS) and phosphor plate systems, that were introduced recently, have the possibility to change the spatial resolution of the system as part of the image acquisition process. For the high resolution solid state sensors this means that pixel-binning is applied in the 'standard resolution' settings (the process of pixel-binning involves taking square groups of pixels and combining them into one 'super' pixel. This might have the effect of reducing required exposure times or improving the signal-to-noise ratio. However, it also reduces the image resolution). For the phosphor plate systems the relative speed of the plate in the scanner can be reduced, as well as the focal spot of the laser beam can be decreased to obtain a higher scanning resolution.

The option to change the resolution settings of a digital imaging system may have effect on the diagnostic accuracy for caries diagnosis and it certainly will have effect on the dimensions of the displayed radiograph. The size of the image displayed on the monitor may even exceed the dimensions of the monitor screen. In order to view the whole image, the magnification at which the image is displayed is then reduced, which may counteract the potential benefits of the increased image resolution of the imaging device.

In view of the above, the aim of our study is (1) to compare the diagnostic accuracy of the high resolution setting and the standard resolution setting of four digital imaging systems (2 CCD and 2 phosphor plate systems) for proximal caries diagnosis, and (2) to compare the effect on the diagnostic accuracy of reducing the high resolution images to the standard resolution dimensions and vice versa. Additionally, we compared the performance of the individual systems used in this study.

The null hypothesis to be tested was that no significant differences exist between the high resolution and standard resolution settings of the systems and that no significant differences occur when reducing the size of the high resolution images or enlarging the standard resolution images.

The model used to compare the various modalities and systems was the diagnostic performance of the digital systems with respect to the diagnosis of proximal caries.

MATERIALS & METHODS

Image acquisition

Ninety extracted human premolars were selected. Based on visual and radiographic examination the proximal surfaces of these premolars ranged from sound to dentinal lesions. The teeth were mounted in groups of five in plaster blocks (four teeth to be examined by the observers and one for a natural contact point). Two blocks at a time were placed in a jig to simulate a bitewing radiograph. Nine different bitewing-sets were radiographed, with a total of 72 different premolars to be examined.

Between the tube end of the X-ray source and the tooth blocks a 30 mm thick soft tissue equivalent material was placed, consisting of 8 mm Lucite and 22 mm water. Exposures were made using a Siemens Heliodent MD X-ray unit (Siemens, Bensheim, Germany) operating at 60kVp, 7mA with a filtration of 1.5 mm Al equivalent. The focus-detector distance was 30 centimeters. The exposure time was 0.25 sec. for the phosphor plate systems and 0.12 sec. for the CCD-systems.

The radiographs were taken using four digital detector systems, 2 CCD-systems and 2 SPP-systems (Table 1). The original manufacturers' software of all four systems was used to acquire the radiographs and no image processing was applied else than the standard pre-processing of the systems themselves.

Table 1: Overview of the systems used in this study.

CCD or SPP	*manufacturer*	*type*	*manufacturer data*	*standard resolution (LP/mm)*	*high resolution (LP/mm)*
CCD	Planmeca	Dixi 2 v3	Planmeca Oy, Helsinki, Finland	13	26
CCD	Gendex	Visualix HDI	Gendex Dental Systems, Des Plaines, Illinois, USA	11,4	22,7
SPP	Dürr	VistaScan	Dürr Dental GMbH&CO. KG, Bietigheim-Bissingen, Germany	10	20
SPP	Soredex	Digora Optime	Soredex, GE Healthcare, Tuusula, Finland	7,8	12,5

All systems have the possibility to change spatial resolution settings. Exposures were made using both resolution settings of each system. This resulted in eight series (4 systems * 2 resolution settings) of nine bitewing simulations.

The original high resolution images were reduced in size using the bi-cubic convolution method; the resulting image was exactly the size of the standard resolution originals. The original standard resolution images were enlarged using the bi-cubic convolution method to exactly meet the size of the high resolution originals. Bi-cubic convolution is an interpolation method that uses two polynomials to define the weighting coefficient for sixteen (4x4) surrounding pixels.[11] Several studies confirm that the bi-cubic convolution method better approximates the original image than other methods such as bilinear interpolation or nearest neighbour interpolation.[12,13]

Observation sessions

The radiographs were displayed on a 20-inch Philips Brilliance 200P TFT monitor (Philips, Eindhoven, The Netherlands) at a resolution setting of 1600x1200 pixels.

The original and resized radiographs were randomly shown to the observers in two random sessions. One session contained all 'standard size' radiographs: both the originals and the high resolution radiographs that were reduced in size. The other session contained all 'large size' radiographs: the original high resolution images and the enlarged standard resolution radiographs. The observation sessions took place in a room with dimmed background lighting. The observers were not allowed to change brightness and contrast settings.

Five observers were asked to estimate caries depth on a 4 point scale:

0 = sound proximal surface;
1 = radiolucency in first half of enamel;
2 = radiolucency up to amelodentinal junction (ADJ)
3 = radiolucency into dentine.

Before the start of the sessions the observers were told that the distribution of the lesion-depths was about 25% for each of the four scoring possibilities. Only one tooth surface of each proximal area was assessed, as observations of disease from two surfaces in the same tooth may be statistically dependent on each other.[14]

Histological validation
True caries depth was determined using histological examination. The teeth were mesio-distally sectioned using a Leica SP1600 saw microtome (Leica Microsystems, Nussloch, Germany) into 300 µm slices and examined with a Zeiss Stemi SV 6 stereomicroscope (Carl Zeiss, Oberkochen, Germany) by two experienced investigators. The same 4 point scale was used as presented above. The two investigators independently assessed the teeth. In case of disagreement they made a joint decision.

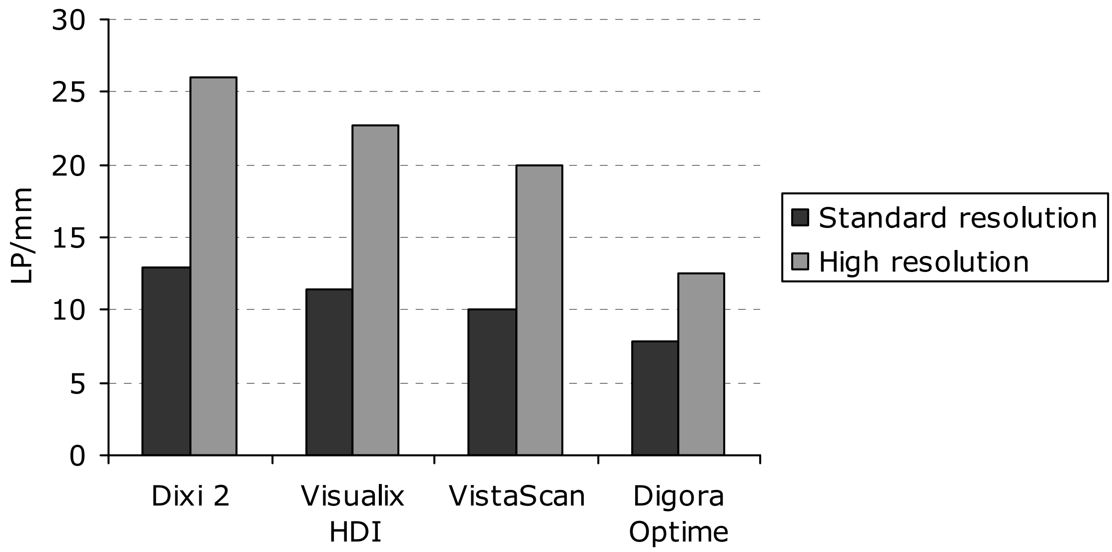
A total of 7 surfaces were excluded from the study because some of these teeth were damaged or had root or occlusal caries. The final material consisted of 65 proximal surfaces from 65 teeth.

Data analysis
The judgments of the five observers are represented in a four-fold frequency table; system * resolution * gold standard * judgment, where judgment represents the dependent variable that measures the probability of detecting the four caries depths. This type of data can be analysed using the statistical theory for multivariate discrete data.[15] In our case the relation between the gold standard and the observers' judgments is crucial. When this relation is ideal the diagnosis is perfect: i.e. sensitivity and specificity are 1.00. When, for example, for two different resolutions the relation to the gold standard is the same, both resolutions have the same diagnostic accuracy, because sensitivity and specificity depend on the relation between gold standard and observers' judgment. For all tests a significance level of $\alpha = 0.05$ is used. Differences were considered statistically significant when $p \leq 0.05$. Cohen's kappa was used to determine the agreement with the gold standard.[16]

RESULTS

The theoretical spatial resolution of the systems used for this study differs to a great extend as shown in Figure 1. The highest resolution for the Soredex (Digora Optime) ('super') is comparable to the standard resolution of the two CCD-systems.

Figure 1. Theoretical spatial resolution of the four systems used, expressed as LP/mm



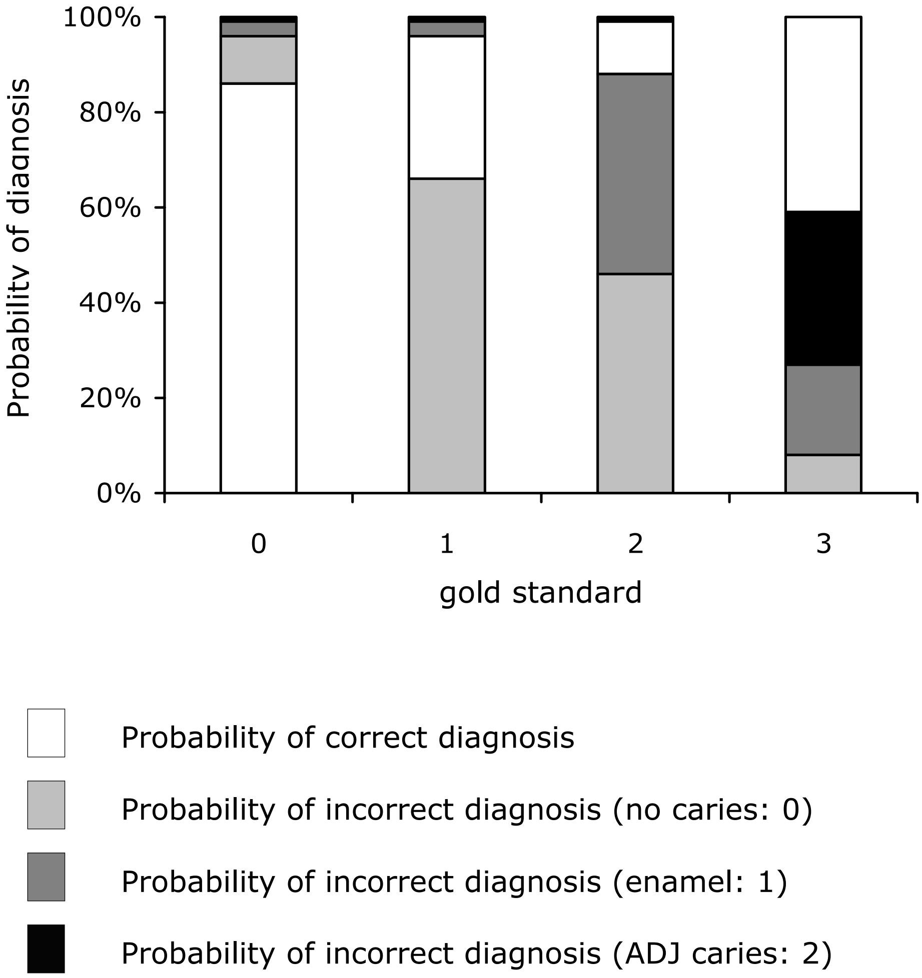
The distribution of the lesion depths based on the histological examination is presented in Table 2.

Table 2: Number and percentages of surfaces per caries depth category.

True lesion depth (histology)	*Number of surfaces*	*Percentage of surfaces*
0	17	26%
1	15	23%
2	12	19%
3	21	32%

Figure 2 is the graphical representation of the overall table of the probability of caries diagnosis (n = 5200) (65 surfaces * 4 systems * 4 resolution conditions * 5 observers = 5200 judgments) and shows the probability of diagnosis given the gold standard. This overall table is referred to frequently in the results section of this manuscript. The white part of each bar is the probability of correct diagnoses given the gold standard. The overall measure of agreement (κ) with the gold standard was 0.27. The gray-shaded bar-parts represent the probability of incorrect diagnosis.

Figure 2: Overall probability of caries diagnosis.



The statistical comparison between the *original high* resolution settings and the *original standard* resolution settings of the four systems showed no difference in the probability of caries detection (χ^2 = 26.59, df = 26, p ~ 0.50). The comparison between *original high* resolution and the standard resolution images that were *enlarged* neither showed significant differences in the probability of caries detection; the comparison between the *original standard* resolution images and the high resolution images that were *decreased in size* did not show a significant difference as well (χ^2 = 26.59, df = 26, p ~ 0.50).

However, the four digital systems used in this study differ significantly in the probability of caries detection (χ^2 = 41,55, df = 24, p < 0.02). Compared to the gold standard the Gendex Visualix HDI CCD-sensor has the highest measure of agreement (κ = 0.31). The differences in the probability of caries detection between the four systems used in this study are displayed in Figure 4. An example of such a graph, together with an explanation is given in Figure 3. The bar with the thick frame is the caries depth according to the gold standard; in this case dentin caries (score 3).

Figure 3: Interpretation of the results for the Visualix HDI, condition dentin caries, according to the gold standard.

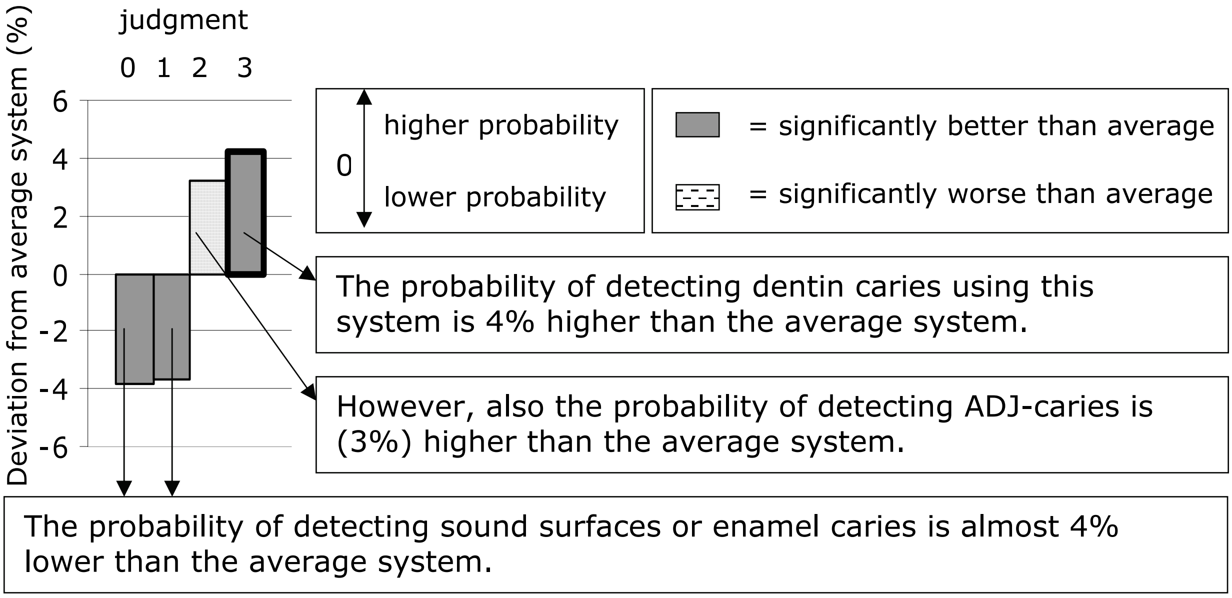


Figure 4. Differences in probability of caries detection between the systems (%)

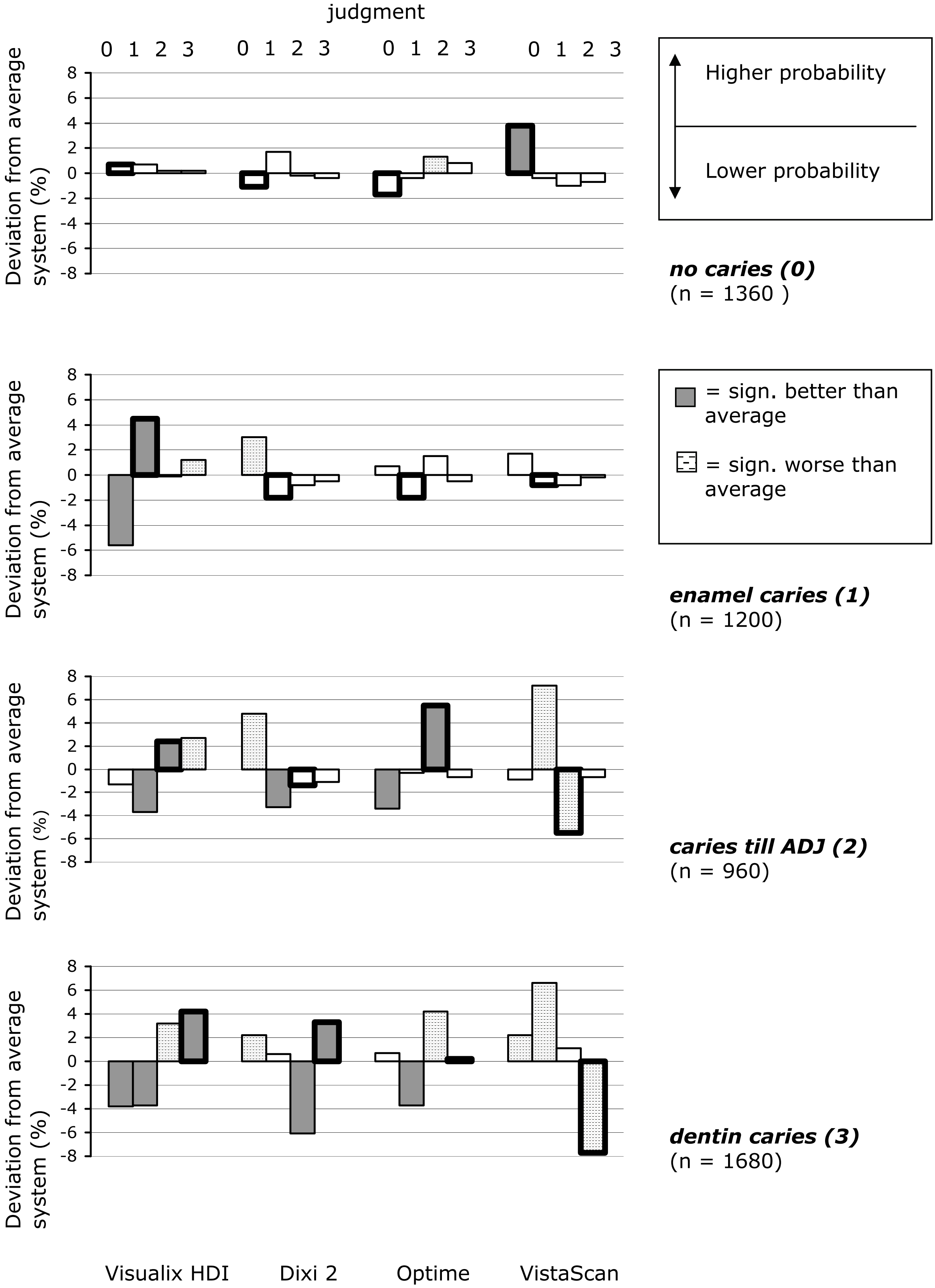


Figure 4 shows the probability of the four systems under investigation for the detection of *sound surfaces* (upper graph), *enamel caries* (second graph), *caries up to the amelodentinal junction* (third graph) and for *dentin caries* (lower graph). The vertical axis represents the difference from the average probability of the four systems. The bars with a thick frame represent the correct diagnosis. A white bar is a non-significant difference compared to the overall table; a grey bar is a significant difference indicating a higher probability of agreement with the gold standard and a bar filled with a pattern of 'minus'-signs represents a significant difference indicating a lower probability of agreement with the gold standard. A grey bar below the horizontal axis of the graph indicates the probability of an incorrect diagnosis is lower. A bar above the horizontal axis filled with 'minus'-signs indicates that the probability of an incorrect diagnosis is higher.

Concerning the probability of correctly diagnosing the *no caries* condition (sound surfaces) (Figure 4, upper graph) the performance of the four systems is quite comparable. The Dürr VistaScan system is better than the other three systems, the Digora Optime has a slight but significantly higher probability of *incorrect* diagnoses (i.e. score 2).

For *enamel caries* the Gendex Visualix HDI outperforms the other three systems with a significantly higher probability of correct diagnoses. Moreover, the Visualix HDI has a significantly lower probability of not diagnosing enamel caries as a sound surface. However, the Planmeca Dixi 2 has a significantly higher probability of diagnosing sound surfaces as enamel caries.

For *caries till the amelodentinal junction* the Digora Optime performs best with a significantly higher probability on correct diagnoses and a significantly lower probability of incorrectly diagnosing sound surfaces. The Gendex Visualix HDI also performs significantly better than the average on amelo-dentinal caries detection and lower on enamel caries detection. However, the system falsely gives a significantly higher probability for dentin caries diagnosis. The Planmeca Dixi 2 has a significantly higher probability on incorrect sound surface diagnosis when caries till the amelodentinal junction is presented to the obervers.

Caries till the amelodentinal junction as well as *dentin caries* are underestimated by the Dürr VistaScan: for both depth-categories a lower probability is achieved than the other systems and a (falsely) higher probability for sound surfaces and enamel caries. However, both CCD-systems have a significant better probability on correct *dentin caries* diagnosis and lower probabilities in falsely diagnosing surfaces. The Digora Optime tends to underestimate dentin caries compared to the CCD-systems by falsely giving higher probabilities to ADJ-caries.

DISCUSSION

Display of a radiograph at image size ratios other than 1:1 means some kind of image processing is applied to the image. Increasing the size of an image (or: zooming in) creates pixels on the monitor screen that are not represented by a pixel on the digital sensor. The way this ‘interpolation’ is done influences the diagnostic value of a digital radiograph.[13] This study shows that 50% increasing or reducing the size of a radiograph using bi-cubic convolution does not affect the diagnostic value for caries diagnosis. Studies on diagnostic value of digital systems should describe at which ratio the radiographs are presented to the observers, as well as the interpolation method that is used (if applicable). Also developers of software coupled to digital radiography systems should report the interpolation method that is used in their software.

A study by Janhom *et al.* using radiographs that were scanned at different resolution settings, showed a resolution effect on the assessment of lesion depth.[8] That seems in contradiction with our results. However in their discussion they admit that there were significant interaction effects between observer, resolution and lesion depth, which might be responsible for the difference found. So they hesitated in concluding that there is significant difference in caries diagnosis between the resolution settings.

The absence of an effect of spatial resolution settings on caries diagnosis does not mean that high spatial resolutions are useless. For example, fine endodontic files might be visualized better with high resolution settings. In our study however, we found that for caries diagnosis the standard settings for all systems performed equally well. An inherent advantage of the standard settings is that the file size of the image remains smaller for storage and transmission.

The displayed image size as used in this study did not have an effect on the accuracy of caries diagnosis. Other studies on this subject showed that only very large magnification and reduction affected the accuracy of caries diagnosis.[13,14] The rescaling of the images in those studies, however, was much larger than what we used in our study.

No image post-processing was applied to the images in this study. Image processing (for example adjustment of contrast and/or brightness) could improve the quality of the displayed image. However, the effect of image processing varies per system and the effect of image processing methods on the accuracy of caries diagnosis was outside the scope of the current study.

On the other hand some systems do apply pre-processing to the raw data that are retrieved from the sensor or phosphor plate. This pre-processing can not be influenced by the user of the system and therefore is reflected in the results of this study. The manufacturer of the VistaScan system claims that no pre-processing is applied to the raw image. This might explain the performance of the VistaScan system which was worse compared to the other three systems. In our opinion the original image of a digital system should be the best image possible with the system. It should not be necessary to apply filters or to manually process the image for the most common diagnostic tasks such as caries diagnosis and endodontic working length estimation. This facilitates an easy handling of the system, with no need of extensive user interaction. Moreover, the user is free to choose the software he prefers to display and store the digital radiographs without being tied to the software of the hardware-manufacturer because of special filters to improve the original image to a useful level.

In conclusion, the probability of correct caries diagnosis is not affected by the setting of the spatial resolution of the digital radiography systems tested, neither by enlarging or reducing in size the images using bi-cubic convolution. High resolution images did not perform better than the images acquired at the low resolution settings. However, the make of the system does affect the probability of caries detection in general. In this study the Gendex Visualix HDI CCD-sensor outperformed the other three systems with respect to agreement with the gold standard, which was represented by more ‘bars’ in the graphs indicating a better performance than the average of the for systems.

APPENDIX - description of the statistical analysis

For a clear and concise description of the statistical analysis it is necessary to go back to the central theme of the present investigation; what factors or variables do influence the sensitivity and specificity of caries detection? In order to answer this question the presence of caries has to be measured somehow. In the present investigation this is done using a four point scale. The points on this scale are representing the perceived depth of the caries lesion. For each tooth used in the study a golden or true caries score was determined using histological examination. This examination leads to the same possible scores (0,..,3). So in the present investigation the judgment of a number of observers is compared with the results of the histological examination.

The basic data can be represented in a cross tabulation like Table 3 (next page). This table represents the overall cross tabulation for the present investigation; this cross tabulations includes all observers, X-ray equipment and image resolutions. As can be seen this table contains all the necessary information to compute the sensitivity and specificity of the measurement procedure. It can also be used to compute the agreement of the judgments with the golden standard; i.e. to compute Cohen's kappa. An important aspect of the measurement procedure is that only minimal assumptions about the measurement level of the judgments are necessary. It is only necessary to assign one of the possible scores to each element. Thus only a nominal measurement level is assumed.

The cross tabulation in Table 3 is a two dimensional frequency table. For each combination of observer, X-ray equipment and image resolution such a cross tabulation can be made. In this case we have a 5 dimensional cross tabulation or frequency table. Statistical theory is available to test for statistical significant differences between (for example) differences between the golden standard $\times$ judgment cross tabulation of the different image resolutions.[15, 16]

Table 3: Overall cross tabulation for the golden standard and judgments.

Gold * Judgment Crosstabulation

			Judgment				Total
			No caries	Enamel caries	Caries enamel dentin junction	Dentin caries	
Gold	No caries	Count	1167	142	38	13	1360
		% within Gold	85.8%	10.4%	2.8%	1.0%	100.0%
	Enamel caries	Count	795	366	33	6	1200
		% within Gold	66.3%	30.5%	2.8%	.5%	100.0%
	Caries enamel dentin junction	Count	437	399	113	11	960
		% within Gold	45.5%	41.6%	11.8%	1.1%	100.0%
	Dentin caries	Count	131	317	535	697	1680
		% within Gold	7.8%	18.9%	31.8%	41.5%	100.0%
Total		Count	2530	1224	719	727	5200
		% within Gold	48.7%	23.5%	13.8%	14.0%	100.0%

In the example given we have four two-dimensional tables like the one in Table 3; one table for each spatial resolution. Now the likelihood χ^2-test can be used to test whether these four tables are different. If the test result is not significant then the four tables are equal. This also implies that the sensitivity and specificity of the caries detection method does not depend on the spatial resolution; the tables are equal and as a result computations that are based on the frequencies in these tables will lead to the same result, at least within random fluctuation.

Because the χ^2-test is an omnibus or overall test, further steps are necessary when a statistical significant result is found. In this case we know that there is a statistical significant difference but we have to find out where the differences are. In the present investigation the binomial test is used to test for differences between proportions. For example in Table 4 (next page) the golden standard $\times$ judgment cross tabulation for the Gendex Visualix HDI X-ray equipment is given.

Table 4: Cross tabulation for the golden standard and judgments of the Gendex Visualix HDI.

Gold * Judgment Crosstabulation

			Judgment				Total
			No caries	Enamel caries	Caries enamel dentin junction	Dentin caries	
Gold	No caries	Count	294	33	9	4	340
		% within Gold	86.5%	9.7%	2.6%	1.2%	100.0%
	Enamel caries	Count	182	105	8	5	300
		% within Gold	60.7%	35.0%	2.7%	1.7%	100.0%
	Caries enamel dentin junction	Count	106	91	34	9	240
		% within Gold	44.2%	37.9%	14.2%	3.8%	100.0%
	Dentin caries	Count	17	64	147	192	420
		% within Gold	4.0%	15.2%	35.0%	45.7%	100.0%
Total		Count	599	293	198	210	1300
		% within Gold	46.1%	22.5%	15.2%	16.2%	100.0%

Now we check whether the Visualix HDI differs from the average equipment. The cross tabulation for the average equipment is given in Table 3. Using the binomial test we compare the proportions in Table 4 with the corresponding proportions in Table 3.

From the foregoing we can conclude that using statistical theory for multivariate frequency tables we can do an elegant statistical analysis of the factors that influence caries detection. It gives rather detailed results, can be used to assess the agreement with the golden standard and uses minimal assumption about the measurement level of the dependent variable.

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8

Discussion,
General conclusions
and
Summary

DISCUSSION, GENERAL CONCLUSIONS and SUMMARY

Digital radiography was introduced in dentistry in the early 80's. Since then, the number of users has increased continuously. Nowadays, digital radiography is a well accepted technology in dental imaging. Radiographic imaging is an essential tool in dental diagnosis. For many decades radiographic films were utilized to acquire the radiographic images. Films are now replaced by various types of digital sensors. The research described in this thesis is carried out to obtain more insight in the consequences of this new technology with respect to image quality, dose to the patient, and other factors influencing the way dental radiology is practiced in dentistry.

The research presented in this thesis is focusing on the most important parameters that should be taken into account when implementing digital radiography in general dental practice. It also emphasizes how those parameters influence the radiation dose and the diagnostic performance of digital radiography in comparison with conventional film based imaging.

In the current chapter the results and conclusions of the preceding chapters will be brought together. Interactions between the various parameters will be discussed and their importance with regard to the implementation of digital radiography in general practice will be stressed. Although digital radiography is available for general dentistry for about twenty years now, the vast majority of general practitioners have not switched to digital radiography yet. The outcome of our studies may also give more insight into the reasons why dentists decide to move to digital imaging or stick to film based radiography.

The diagnostic process based on digital radiography includes many more parameters than film based radiography. Therefore, the introduction of digital radiography may have caused a renewed interest in the efficacy of diagnostic imaging. Already in the 1970's a conceptual framework was designed to evaluate and compare the efficacies of diagnostic tests.[1-4]

In 1991 Fryback and Thornbury presented a model that distinguishes six levels of efficacy that range from the technical efficacy of a system (level 1) to the societal efficacy (level 6).[5] This thesis mainly deals with the first level (technical efficacy) and second level (diagnostic accuracy) although the dose effects can be scaled into level five (patient outcome efficacy) of the model as well. A key feature of the hierarchy of this model is the understanding that for an imaging procedure to be efficacious at a higher level it must be efficacious at lower levels, but the reverse is not true. Increases in the efficacy at a lower level (e.g., technical image quality) will not guarantee improvement at higher levels (e.g., patient outcome). Therefore this general discussion will try to link the studies in this thesis together with the patient outcome and societal level of the model.

Chapter 2 gives an overview of the research described in this thesis, starting with the basic differences between film and digital sensors, i.c. the silver bromide crystals and the pixels (picture elements). The terms contrast resolution (number of gray levels) and spatial resolution (number of pixels per inch or millimeter) are described together with an introduction of digital radiography (*see also Chapter 7*). Because of the digital nature of the images, this allows us to describe the diagnostic efficacy in radiology depending on the physical characteristics of pixels and how their information is manipulated, automatically as well as by the user of the system.

The diagnostic efficacy of digital systems has frequently been compared with film based radiography in the past twenty years. For the detection of caries lesions the general conclusion is that no differences in diagnostic performance exist between film and digital systems. Image enhancement of digital radiographs might help improve caries diagnosis.[12] In endodontology (length of file size determination) at least file size 15 is necessary to make digital systems as accurate as film.[6-8] For the detection of periapical lesions as well as periodontal lesions digital systems and film perform equally well.[9-11]

Another approach to evaluate the utility of digital systems is to ask experienced dentists or dental radiologists for their opinion about image quality. Especially in situations where histological validation is not possible (for instance in clinical studies) this subjective approach is a useful method to compare digital radiographic systems mutually and with film (see also *Chapter 5 and 6*).

One of the benefits of digital radiography is the possibility of image enhancement. Many parameters of a digital image can be manipulated to make the image more suitable for specific diagnostic tasks. However, in the literature from the past twenty years only for caries diagnosis an improved diagnostic accuracy on enhanced digital radiographs was found.[12] In all other (dental) diagnostic fields the results of the many studies on image enhancement are rather divided. Improved diagnostic accuracy was reported[13] however, also deterioration of diagnostic accuracy was found.[14] Most of the studies did not find a difference in diagnostic accuracy between enhanced and original images.

The last paragraph of *Chapter 2* deals with the radiation dose, which is not only determined by the amount of radiation per exposure, but also by the number of radiographs taken (see also *Chapter 4*) and the dynamic range of digital systems (see also *Chapters 5 and 6*). It is quite probable that the claims from manufacturers on dose savings resulting from the implementation of a digital system are not valid to their full extend.

Chapter 3 compares the experiences of general dental practitioners using solid-state and storage phosphor systems to film. A mail survey was used to collect data from Dutch general practitioners about the digital system or film they used and their opinion about the user-friendliness of the imaging systems. We asked the dentists using conventional film what reason they have for not utilizing a digital system. The costs of purchasing a digital system appeared to be the major reason for not (yet) purchasing a digital system, although the idea that no benefits could be expected from a digital system and even the idea that the image quality is too poor also were important factors.

The user-friendliness was divided into eight categories ranging from preparing and positioning the detector to processing, diagnosing, archiving images and system maintenance. It appeared that the digital systems gave significantly lower scores on user friendliness in the preparation and positioning categories whereas with respect to processing, diagnosing, archiving images and system maintenance the digital systems outperformed film in user friendliness. The positioning problems experienced by dentists could in the first place be explained by the stiffness of the digital x-ray detectors and in the second place by the size of the detector (and not having available more then one detector size).

The positioning problems could partly explain the greater number of radiographs taken with digital systems then with conventional film.

Chapter 4 compares the number of radiographs taken in general dental practices equipped with digital radiography and film-based radiography. Solid-state sensor users as well as phosphor plate users take significantly more X-rays then film users. This difference is caused by the number of periapical radiographs because no difference in numbers could be found for bitewing radiographs. A greater number of retakes is partly responsible for the increase in radiographs. Another reason given for the increase in radiographs is the improved diagnostic possibilities without additional radiation compared to film, because the general belief is that digital radiography requires less than half the radiation that is needed for film-based radiography. This idea is firmly backed by the manufacturers and resellers who claim dose savings of their system of up to 90% compared to film, but mostly 'forget' to say that the system is compared to D-speed film.

The possible increase of patient dose due to digital radiographic systems was a reason for concern as expressed by the International Commission on Radiological Protection (ICRP). During the preparation of this thesis the ICRP issued their report about patient dose in digital radiography in 2005.[15] This report mentions the potential risk of digital radiography (medical as well as dental) for patient doses. Because this relatively new technique is advancing rapidly it will soon affect hundreds of millions of patients. It continues that 'If careful attention is not paid to radiation protection issues of digital radiology, medical exposure of patients will increase significantly and without concurrent benefit.' Three reasons are given for this potential increase of patient dose: the greater number of radiographs that is taken because of the relative ease of obtaining an image, perish of diagnostic information by inappropriate image compression and/or post-processing and the dynamic range of digital radiographic systems.

Chapter 5 of this thesis describes a study on the dynamic range of digital dental radiographic systems (both phosphor plate and solid-state sensors) and film. The dynamic range, also called exposure range, is the range of diagnostically acceptable radiographs as a function of exposure time. The results of the study show a very broad dynamic range for phosphor plate systems and a narrow dynamic range for solid-state sensors. Film takes a mid-position. The chapter concludes that both the very broad dynamic range as well as the narrow dynamic range may be of risk for patient dose. The narrow range of solid-state sensor systems might easily cause over- or underexposure because of the relative great influence of the soft tissues on radiation absorption, which makes retakes necessary. The broad dynamic range of the phosphor plate systems easily results in overexposure without an adverse impact on image quality. This overexposure may not be recognized by the dentist. In film-based radiography, excessive exposure produces a "black" film and inadequate exposure produces a "white" film, both with reduced contrast. In digital systems, image brightness can be adjusted by pre- and post processing independent of exposure level. Therefore, image processing to optimize contrast and brightness as part of the scanning process may easily "mask" the overexposure.

The ICRP-report clearly relates the technical aspects of digital radiography to the patient outcome level (5) and societal level (6) as distinguished in the model of Fryback and Thornbury.[5] The committee is concerned about possible increase in patient dose and population dose by digital radiography, because of the reasons mentioned above.

Also in The Netherlands the patient as well as population dose are in the centre of attention. In 2002 in The Netherlands new legislative requirements on radiological protection came in force ('Besluit Stralenbescherming' (BS)). The BS complies with the provisions of Euratom Guideline 96/29 related to the protection of workers and the general public against the effects of radiation and Guideline 97/43 which concern the protection of the individuals against ionizing radiation from medical sources. In 2005 the Dutch National Institute for Public Health and the Environment (RIVM) issued their report describing the number and type of medical examinations and treatments employing ionizing radiation and the exposure of the Dutch population.[16] The RIVM stresses the enormous number of radiographic exposures in the dental field. Although the effective dose per inhabitant is not high, between 1998 and 2003 the number of dental radiographs in the Netherlands has increased from 6 million to 8 million per year. One of the explanations for this is the increase in digital radiographic equipment. Together with the 'dynamic range issue', partly based on the information from Chapter 5 of this thesis, this information is intended to stimulate optimal use of radiation in health care.

The dynamic range of digital system not only influences patient and population dose but might influence diagnostic performance as well. **Chapter 6** of this thesis describes the study on the effect of different exposure settings within the dynamic range of digital systems on diagnostic performance for caries diagnosis. The effect of getting 'nicer' radiographic images at the cost of higher radiation doses might tempt dentists to apply higher doses assuming the 'nicer' radiographic images have more diagnostic value. This study first determines the exposure times resulting in subjectively 'preferred' and 'just acceptable' radiographs and next compares those radiographs for differences in diagnostic performance using a caries model. Determining which exposure level is the 'lowest possible' for digital systems is an important task that follows directly from the ALARA (As Low As Reasonably Achievable) principle and has a strong link to ICRP publication 93.

It was concluded that no difference in diagnostic performance for caries diagnosis exists between preferred ('high' dose) and just acceptable ('low' dose) radiographs. Therefore, the exposure time should be chosen such that the result is subjectively just acceptable radiographs. This recommendation has consequences for the daily use of digital radiographic systems (and film). It means that for different types of radiographs, bitewings, periapicals, front and molar region, from adult or children, different exposure settings are prescribed. When a new radiographic system is implemented in dental practice an exposure table should be made to differentiate between those different exposure conditions.

Chapter 7 shows a new development in digital radiography: the increasing spatial resolution. It is interesting to know if the higher resolution pays off in better diagnostic performance. This chapter describes the study on the effect of standard and high resolution settings of different digital radiographic systems on the diagnostic performance for caries diagnosis. Although all systems show some differences in diagnostic performance we have not found a statistically significantly improved or worsened diagnostic performance for the high resolution settings of the systems compared to the standard resolution settings. Other factors, such as noise in the radiographic image, might have a bigger influence on diagnostic performance than spatial resolution.

In general it can be concluded that in digital radiographic systems many more parameters play a role than in film based radiography. From this thesis can be concluded that several factors should be taken into consideration when implementing a digital radiographic system in dental practice. Many of those factors have an effect on patient and population dose. As shown in chapter 2, 6 and 7 as well as recently in a review of digital radiography[17] diagnosis is not positively or negatively affected when implementing digital radiography. However, as shown in chapter 3, 4 and 5, as well as by the ICRP patient and population dose are affected, which can easily results in increasing doses.

Therefore two main recommendations can be given, one to dentists implementing a digital radiographic system or dentists already using such a system and one to the scientific field and industry.

- When implementing digital radiography in dental practice, a possible increase in radiation dose should be prevented. An increase in the taking of radiographs for the desired diagnostic task easily happens and should be avoided. That process starts with the decision **if** a radiograph is of any help for the diagnosis or expected treatment. Next the appropriate imaging technique should be chosen and carried out in the correct way (for example by using aiming devices when taking an intraoral radiograph). Of course, the lowest exposure level possible for the diagnostic task should be applied. Therefore the use of an exposure table should be a standard procedure in every practice. Next, the image processing should be optimized for the diagnostic task and the diagnosis should be performed by a well trained person.

- The scientific field and industry should stay focused on methods to improve the diagnostic performance without an increase in radiation dose and/or at least keep the diagnostic performance at the current level with reduced radiation dose. The first issue might be possible with increased grayscale resolution which gives more options for image processing and therefore possibly an increased diagnostic performance. The latter mainly depends on improved user-friendliness, as regards positioning the detector as well as guided exposure control.

From this thesis it is clear that currently digital radiography and film based radiography qualitatively are comparable. Digital radiography has the potential of reducing radiation dose, but also the risk of increasing doses. For image management en environmental reasons digital radiography is preferable. Subsequent research in digital radiology should focus on improved diagnostic possibilities over film-based radiology, like systems with higher grayscale resolution giving more options for improved image processing.

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9

Samenvatting

(Dutch summary)

SAMENVATTING

Op 8 november 1895 werd door Wilhelm Conrad Röntgen bij toeval een nieuw soort straling ontdekt, door hem aangeduid met X-straling. Slechts drie maanden na de toevallige ontdekking maakte een Duitse tandarts al de eerste tandheelkundige röntgenfoto. Bijna honderd jaar lang was film die gevoelig is voor röntgenstraling de enige manier om de röntgenschaduw zichtbaar te maken.

In 1987 werd digitale röntgenologie in de tandheelkunde geïntroduceerd. Sindsdien wordt röntgenfilm langzamerhand door steeds meer tandartsen vervangen voor digitale röntgensensoren. Er zijn twee hoofdtypen digitale röntgensystemen te onderscheiden: de CCD- (Charge Coupled Device) en CMOS- (Complementary Metal Oxide Semiconductor) sensoren en de SPP (Storage Phosphor Plate) systemen. De CCD- en CMOS-systemen zijn met een snoer met de computer verbonden en het röntgenbeeld verschijnt enige seconden na de belichting direct op het monitorscherm. Bij de fosforplaatsystemen wordt het latente röntgenbeeld tijdelijk opgeslagen op het fosforplaatje dat daarna met een laserbundel in een scanner worden uitgelezen, en waaruit het röntgenbeeld wordt gereconstrueerd. Digitale röntgenologie is ondertussen een geaccepteerde technologie in de tandheelkundige radiologie.

Het onderzoek dat in dit proefschrift wordt beschreven is uitgevoerd om meer inzicht te verkrijgen in de toepassing van digitale röntgenologie in de algemene tandartspraktijk, voornamelijk met betrekking tot beeldkwaliteit, stralingsdosis voor de patiënt en factoren die de manier beïnvloeden waarop tandheelkundige radiologie in de praktijk wordt toegepast. Het onderzoek spitst zich toe op de belangrijkste parameters waarmee rekening zou moeten worden gehouden als een digitaal röntgensysteem in de algemene tandartspraktijk wordt geïmplementeerd. Het onderzoek beschrijft ook hoe die parameters invloed kunnen hebben op de stralingsdosis en de röntgendiagnostiek.

Hoofdstuk 2 is een overzichtsartikel dat begint met de beschrijving van de verschillen tussen röntgenfilm en digitale röntgensensors, in casu de zilverbromide kristallen versus de pixels (beeldpunten van een digitaal systeem). In de introductie worden de termen 'grijswaarden resolutie' (aantal verschillende grijswaarden dat een systeem kan weergeven) en 'ruimtelijke resolutie' (aantal pixels per inch of millimeter) toegelicht (in hoofdstuk 7 wordt dieper hierop ingegaan in het kader van de invloed van de resolutie op de diagnostiek). De informatie van een digitaal röntgenbeeld wordt opgeslagen per pixel, wat de mogelijkheid geeft om de doelmatigheid van de diagnostiek te relateren aan fysieke instellingen van de pixels en die instellingen automatisch dan wel handmatig te veranderen. Mede door die mogelijkheden, welke niet zo gemakkelijk beschikbaar zijn in de conventionele röntgendiagnostiek met behulp van analoge film, is de röntgendiagnostiek met behulp van digitale röntgensystemen de afgelopen twintig jaar al veelvuldig vergeleken met diagnostiek op conventionele film.

Voor wat betreft cariësdiagnostiek is er tot op heden geen verschil vastgesteld in diagnostische uitkomst tussen film en digitale röntgenologie. Voor de endodontologie, met name voor het bepalen van de lengte van de endodontische vijl, zijn digitale systemen ook vergelijkbaar met film, mits een vijldikte van minimaal maat 15 wordt gebruikt. Ook voor de diagnostiek van periapicale en parodontale laesies zijn film en digitale systemen gelijkwaardig.

Digitale röntgenologie geeft zoals gezegd de mogelijkheid van beeldbewerking. Het röntgenbeeld kan op allerlei manieren beter geschikt worden gemaakt voor een specifieke diagnostische vraagstelling. Echter, de literatuur van de afgelopen twintig jaar heeft alleen voor bewerkte röntgenbeelden voor cariësdiagnostiek een verbetering van de diagnostische uitkomst laten zien. In andere gebieden van tandheelkundige diagnostiek zijn de uitkomsten van beeldbewerking op digitale röntgenbeelden erg wisselend. Er is verbetering van de diagnostiek gerapporteerd, maar ook verslechtering, en de meeste literatuur kan geen verschil aantonen tussen bewerkte en niet bewerkte beelden dan wel film.

In de laatste alinea van hoofdstuk 2 wordt het belang van de stralingsdosis geïntroduceerd. De stralingsdosis is niet alleen afhankelijk van de hoeveelheid straling per röntgenopname, maar logischerwijs ook van het aantal röntgenopnamen en de belichtingsspeelruimte van digitale systemen. Onderzoek naar het aantal opnamen en de invloed van de belichtingsspeelruimte is beschreven in respectievelijk hoofdstuk 4 en de hoofdstukken 5 en 6. Het is zeer aannemelijk dat de uitspraken van fabrikanten betreffende dosisreductie bij gebruik van digitale systemen niet volledig opgaan.

Hoofdstuk 3 beschrijft het onderzoek naar het gebruik van systemen voor digitale röntgenologie in de algemene tandartspraktijk. Het onderzoek vergelijkt de ervaringen van tandartsen die een CCD-sensor of een fosforplaatsysteem gebruiken. 578 Nederlandse tandartsen werd gevraagd een vragenlijst in te vullen met betrekking tot het gebruiksgemak van hun digitale systeem of film. Tandartsen die film gebruiken werd gevraagd waarom ze nog niet over waren gestapt op een digitaal röntgensysteem. De kosten die met de aanschaf van een dergelijk systeem gemoeid zijn bleken de belangrijkste factor om nog niet over te stappen, echter het idee dat een digitaal systeem geen toegevoegde waarde heeft boven film en zelfs dat de beeldkwaliteit van een digitaal systeem slechter is dan film waren ook belangrijke redenen om (nog) niet over te stappen op digitale röntgenologie.

Voor het onderzoek naar het gebruiksgemak van digitale systemen en film werd een indeling gemaakt in acht gebruikscategorieën, variërend van het voorbereiden van het digitale systeem voor de röntgenopname en het positioneren van de röntgendetector in de mond van de patiënt, tot het bewerken en archiveren van de opnamen en het onderhoud van het systeem. Digitale systemen bleken een significant lagere gebruiksvriendelijkheid te hebben dan film voor de handelingen die vóór en tijdens het feitelijk maken van de röntgenopname verricht moeten worden. Het voorbereiden van het digitale systeem houdt in het in een hygiënehoesje plaatsen van de sensor of fosforplaat, het in een instelapparaat plaatsen van de sensor of fosforplaat en het activeren van het computerprogramma dat de sensor aanstuurt. Tandartsen die met film werken gebruiken geen hygiënehoesjes omdat film niet hergebruikt wordt en zij activeren geen computerprogramma, wat de lagere gebruiksvriendelijkheid van digitale systemen op dit punt kan verklaren.

Het positioneren van een sensor of fosforplaat wordt, zoals gezegd, wat betreft gebruiksvriendelijkheid ook lager gewaardeerd dan het positioneren van film. De problemen die tandartsen ondervinden bij het plaatsen van de sensor of fosforplaat in de mond van de patiënt kunnen in

de eerste plaatsen worden verklaard door de onbuigzaamheid van de sensor en fosforplaat en in de tweede plaats door de afmeting van de sensor of fosforplaat en wellicht ook het niet beschikbaar hebben van meer dan één afmeting van de sensor.
De handelingen die uitgevoerd worden ná het maken van de opname, zoals het ontwikkelen dan wel scannen van de röntgenopname, het doen van diagnostiek aan de hand van de opname en het archiveren ervan worden juist significant hoger gewaardeerd voor digitale systemen vergeleken met film. Dit heeft waarschijnlijk te maken met de snelheid van het proces en het gemak van digitale beeldbewerking en opslag.

De problemen die tandartsen ervaren tijdens het positioneren van de sensor of fosforplaat in de mond van de patiënt kunnen een verklaring zijn voor het grotere aantal opnamen dat wordt gemaakt door tandartsen die met een digitaal röntgensysteem werken in vergelijking met hun collega's die film gebruiken. In **hoofdstuk 4** wordt het aantal röntgenfoto's, dat in praktijken met digitale röntgensystemen wordt gemaakt, vergeleken met het aantal röntgenfoto's dat wordt gemaakt in praktijken waar film wordt gebruikt. In praktijken die zijn uitgerust met een CCD-systeem wordt gemiddeld 50% meer röntgenfoto's gemaakt dan in praktijken waar film wordt gebruikt en in praktijken met een fosforplaatsysteem worden 30% meer opnamen gemaakt. Het verschil tussen praktijken met een digitaal röntgensysteem en praktijken die film gebruiken wordt veroorzaakt door de periapicale opnamen, want het aantal bitewingopnamen dat wordt gemaakt is voor beide groepen nagenoeg gelijk.

De toename van het aantal opnamen wordt deels veroorzaakt door een groter aantal opnamen dat moet worden overgemaakt. Daarnaast noemen de tandartsen de toegenomen diagnostische mogelijkheden "zonder extra stralingdosis voor de patiënt" als reden om eerder of extra röntgenopnamen te maken. De gedachte dat er geen extra stralingsdosis ten opzichte van film zou zijn wordt ondersteund door het algemene idee dat digitale röntgenologie ten opzichte van film gemiddeld slechts de helft van de hoeveelheid straling vergt. Dit idee wordt volop ondersteund door de fabrikanten en verkopers van digitale systemen, die beweren dat hun systeem vergeleken met film tot wel 90% stralingsreductie geeft, waarbij doorgaans echter wordt 'vergeten' te vertellen dat het systeem vergeleken is met D-speed film.

De mogelijke toename van de stralingsdosis voor patiënten ten gevolge van het gebruik van digitale röntgensystemen was reden tot bezorgdheid voor de ICRP (International Commission on Radiological Protection). In 2005 bracht de ICRP een rapport uit over de stralingsdosis in digitale röntgenologie. Dit rapport geeft het mogelijke risico aan dat digitale röntgenologie (medisch en tandheelkundig) heeft voor de dosis voor de patiënt. Omdat digitale röntgenologie snel terrein wint ten opzichte van film zullen op relatief korte termijn honderden miljoenen patiënten ermee te maken krijgen. Het rapport vervolgt dat 'als er niet voldoende aandacht wordt gegeven aan stralingsbescherming in relatie tot digitale röntgenologie, de stralingsdosis voor patiënten significant zal toenemen zonder toegenomen (diagnostisch) voordeel voor de patiënt.
Het rapport geeft drie oorzaken voor de potentiële toename van de patiëntdosis:

- Het groter aantal röntgenopnamen dat wordt vervaardigd vanwege het relatieve gemak van het maken van een digitale röntgenopname,
- Het verdwijnen van diagnostische informatie ten gevolge van verkeerde beeldcompressie en/of beeldbewerking,
- De 'dynamic range' (belichtingsspeelruimte) van digitale röntgensystemen.

In **Hoofdstuk 5** wordt het onderzoek naar de belichtingsspeelruimte van digitale röntgensystemen beschreven. De 'dynamic range' (belichtingsspeelruimte) is het belichtingsgebied (bijvoorbeeld als functie van de belichtingstijd) waarbinnen door een digitaal systeem voor diagnostiek bruikbare röntgenopnamen worden geproduceerd. De resultaten van het onderzoek laten een zeer brede belichtingsspeelruimte zien voor fosforplaatsysteem en een smalle voor CCD-systemen, film zit ertussenin. Zowel de brede als de smalle belichtingsspeelruimte van digitale systemen veroorzaken een potentieel risico voor de patiëntdosis. De smalle belichtingsspeelruimte kan gemakkelijk verlies aan beeldkwaliteit door over- of onderbelichten veroorzaken vanwege de relatief grote invloed van de weke delen op de stralingsabsorptie. Dit kan het overmaken van opnamen nodig maken.

Bij de brede belichtingsspeelruimte kan ongemerkt worden overbelicht, omdat overbelichten geen slechter röntgenbeeld oplevert, waardoor de patiëntendosis dus ongewild hoger wordt dan nodig is. Bij film veroorzaakt overbelichten een veel te donkere en onderbelichten een te lichte röntgenfoto, beide met verminderd contrast. In de digitale röntgenologie kan de helderheid van het röntgenbeeld middels beeldbewerking worden aangepast (automatisch door de computer tijdens het scannen van de opname of handmatig door de tandarts). Door het optimaliseren van helderheid en contrast kan beeldbewerking belichtingsfouten maskeren.

Het eerder genoemde ICRP rapport legt een duidelijk verband tussen deze technische aspecten van digitale röntgenologie en het effect ervan op de patiëntdosis en de bevolkingsdosis. De commissie is bezorgd over de mogelijke toename van zowel de dosis voor de individuele patiënt als wel de bevolkingsdosis door het gebruik van digitale röntgenologie.

Ook in Nederland staan de dosis voor de patiënt en de bevolkingsdosis in het middelpunt van de belangstelling. In 2002 werd het nieuwe Besluit Stralenbescherming van kracht. Dit Besluit Stralenbescherming is gebaseerd op de Euratom richtlijnen 96/29 en 97/43 die respectievelijk de bevolkingsdosis en patiënt dosis als aandachtspunt hebben. Het Rijksinstituut voor Volksgezondheid en Milieu (RIVM) bracht in 2005 een rapport uit betreffende het aantal en soort medische röntgenonderzoeken en de stralingsbelasting van de Nederlandse bevolking ten gevolge daardoor. In het rapport benadrukt het RIVM het grote aantal röntgenopnamen dat door tandartsen wordt vervaardigd. Hoewel de effectieve dosis per inwoner ten gevolge van tandheelkundige röntgenstraling niet hoog is, is het aantal tandheelkundige röntgenopnamen tussen 1998 en 2003 gestegen van 6 miljoen naar 8 miljoen per jaar. Een van de verklaringen hiervoor is de toename van het aantal digitale röntgensystemen. Het rapport van het RIVM, deels gebaseerd op het onderzoek dat in hoofdstuk 5 van dit proefschrift is beschreven, is bedoeld om het optimale gebruik van röntgenstraling in de gezondheidszorg te bevorderen.

De belichtingsspeelruimte van digitale röntgensystemen beïnvloedt de patiëntdosis en bevolkingsdosis maar wellicht ook de diagnostiek. In **Hoofdstuk 6** van dit proefschrift wordt het onderzoek naar het effect van de belichtingstijd binnen de belichtingsspeelruimte op cariësdiagnostiek beschreven. Het gevolg van het verkrijgen van voor het oog mooiere röntgenbeelden door langer te belichten zou tandartsen ertoe kunnen verleiden langere belichtingstijden te gebruiken in de veronderstelling dat mooiere röntgenbeelden ook een hogere diagnostische waarde hebben.

In dit onderzoek wordt eerst bepaald welke belichtingstijd volgens de waarnemers de diagnostisch meest optimale en de diagnostisch nog net bruikbare röntgenopname oplevert. Vervolgens wordt gekeken of er verschil is in de correctheid van cariësdiagnostiek tussen deze twee belichtingstijden. De conclusie luidt dat er geen verschil in de correctheid van de cariësdiagnostiek is tussen de optimale en de net bruikbare röntgenopnamen. Als gevolg daarvan zal door tandartsen gestreefd moeten worden naar het toepassen van belichtingstijden die voor het oog net bruikbare röntgenfoto's opleveren. Deze aanbeveling heeft gevolgen voor het dagelijkse gebruik van digitale röntgensystemen en film. Het houdt in dat voor verschillende soorten opnamen (bitewings of periapicale opnamen, front of molaargebied, voor volwassen of kinderen) verschillende belichtingstijden moeten worden gebruikt. Als een nieuw röntgensysteem in de praktijk wordt geplaatst, zal een belichtingstabel moeten worden gemaakt die de genoemde soorten opnamen en condities onderscheidt.

Hoofdstuk 7 behandelt een nieuwe ontwikkeling in de digitale radiologie: de toename van de ruimtelijke resolutie van de röntgenbeelden. Dit hoofdstuk beschrijft het onderzoek naar het effect van een hogere ruimtelijke resolutie op de correctheid van cariësdiagnostiek. Met verschillende digitale systemen, CCD- en fosforplaatsystemen, waarbij de ruimtelijke resolutie van het beeld bij het maken of scannen van de opname kon worden ingesteld, werden röntgenopnamen gemaakt van een cariësmodel. Waarnemers beoordeelden de hoge en lage resolutie opnamen op de aanwezigheid en diepte van cariëslaesies. Hoewel de systemen onderling wat verschilden in de correctheid van de cariësdiagnostiek, werd geen significant verschil tussen de hoge en lage resolutie opnamen gevonden. Andere factoren, zoals ruis in het röntgenbeeld, hebben een grotere invloed op de diagnostiek dan de ruimtelijke resolutie.

In het algemeen kan worden geconcludeerd dat in de digitale röntgenologie meer variabelen een rol spelen dan bij de röntgendiagnostiek door middel van röntgenfilm. Uit dit proefschrift volgt welke factoren een rol spelen bij de implementatie van een digitaal röntgensysteem in de tandartspraktijk en in welke mate. Een aantal van deze factoren heeft invloed op de patiëntdosis en bevolkingsdosis. Zoals uit recent onderzoek door collega-onderzoekers en uit hoofdstuk 2, 6 en 7 van dit proefschrift blijkt wordt de tandheelkundige röntgendiagnostiek niet positief of negatief beïnvloed door het overgaan op digitale röntgenologie. Echter uit hoofdstuk 3, 4 en 5 evenals uit het rapport van de ICRP blijkt dat de patiënt- en bevolkingsdosis wel negatief beïnvloed kan worden.

Verder onderzoek in de digitale tandheelkundige radiologie zou daarom gericht moeten zijn op het verkleinen van de kans op toenemende stralingsdosis en tegelijkertijd op het verhogen van de diagnostische opbrengst van een röntgenopname bij gelijkblijvende of lagere dosis. Digitale systemen met een hogere grijswaardenresolutie, wat meer mogelijkheden voor beeldbewerking geeft, zouden daaraan kunnen bijdragen.

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Dankwoord

(Acknowledgments)

DANKWOORD

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CURRICULUM VITAE

Wolter Erwin Rogier Berkhout werd op 25 oktober 1974 in Zeist geboren.
In 1993 behaalde hij zijn middelbare school diploma aan het Gemeentelijk Gymnasium in Apeldoorn, waarna hij tandheelkunde ging studeren aan het Academisch Centrum Tandheelkunde in Amsterdam. Naast zijn studie heeft hij zich beziggehouden met het geven van zeilopleidingen, zowel bij zeilschool Oer 't Hout in Grou, Friesland als bij de overkoepelende organisatie van zeilscholen, het CWO (Commissie Watersport Opleidingen). In dat kader heeft hij vele didactiek cursussen gevolgd en gegeven en was hij eindverantwoordelijk voor de kwaliteit van de opleidingen van de genoemde zeilschool.
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In 2000 is Erwin begonnen met het doen van onderzoek in het kader van een AIO-aanstelling.
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